

AD-A167 342

DEVELOPMENT OF AIRBORNE ELECTRIC FIELD AND LIGHTNING
DETECTION INSTRUMENTATION FOR AVIATION SAFETY(U)
WEATHER CORP WESTON MA R MARKSON 20 APR 86

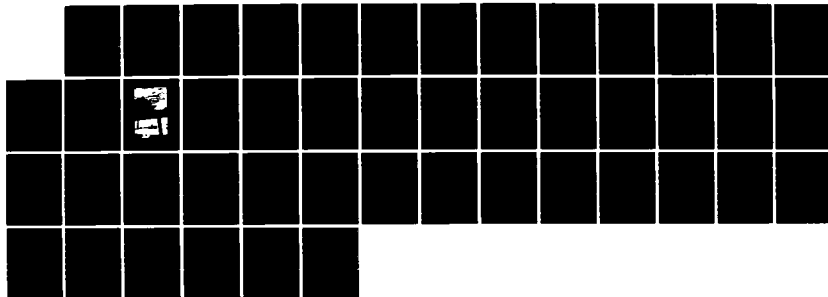
1/1

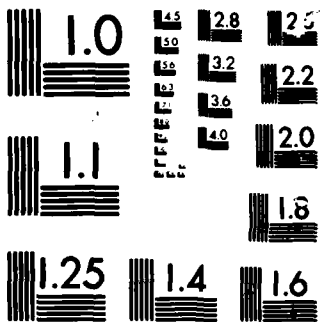
UNCLASSIFIED

N00014-85-C-0707

F/G 1/4

NL





MICROCOPY

CHART

AD-A167 342

2

OFFICE OF NAVAL RESEARCH

SMALL BUSINESS INNOVATION RESEARCH PROGRAM

CONTRACT N00014-85-C-0707

PHASE I

FINAL REPORT

Development of Airborne Electric Field and
Lightning Detection Instrumentation for Aviation Safety

Ralph Markson
Weather Corporation
46 Kendal Common Road
Weston, Massachusetts 02193
(617)899-1834



20 April 1986

This document has been approved
for public release and sale; its
distribution is unlimited.

Notice: Information contained in this final report is confidential and has potential commercial use for development of new products. It is furnished to the Government in confidence with the understanding that it will not, without permission of Weather Corporation, be used or disclosed other than for evaluation and for contract obligation purposes.

DTIC FILE COPY

86-4 23 049

CONTENTS

A.	INTRODUCTION AND SUMMARY.....	3
B.	ELECTRIC FIELD MEASUREMENTS.....	5
	-- Laboratory Studies of Corona Instrumentation.....	5
	-- Testing During Field Programs and Scientific Results.....	6
	-- Discussion of Electric Field Data.....	7
C.	LIGHTNING INTERFEROMETER FEASIBILITY STUDY by Arthur Uhler.....	9
	-- Introduction.....	9
	-- General Features of the Method.....	9
	-- Propagation Calculations.....	12
	-- Path Differences.....	12
	-- Reflectivity of Sea Water.....	13
	-- Effect of Waves.....	14
	-- Divergence.....	15
	-- Relative Magnitude of Reflection.....	15
	-- Antenna Considerations.....	16
	-- Signal Characteristics and Processing.....	16
	-- Analog-to-Digital Converter Specifications.....	19
	-- Experiments on Lightning.....	20
	-- Electronic Components.....	21
	-- Conclusions.....	23
	-- References.....	25
	-- Appendix A.....	26
	-- Symbol Table.....	26
D.	RECOMMENDATIONS FOR PHASE II.....	29
	-- Radioactive Probe D.C. Electric Field Sensing System.....	29
	-- Lightning Interferometer.....	29

A. INTRODUCTION AND SUMMARY

At present there are two methods for thunderstorm avoidance (1) weather radar which senses rain and (2) the Stormscope which senses lightning position. The proposed lightning interferometer offers several advantages over both systems. While with an unobstructed view radar can see heavy rain at ranges of 100 miles or more and lighter rain when closer, radar signals are attenuated by precipitation from closer clouds which mask more distant rain. Moreover, rain per se does not necessarily imply the presence of thunderstorms nor do all thunderstorms produce heavy rain. In addition, many aircraft, military as well as civilian (particularly single engine), have no convenient location for radar antennas. Radar also requires appreciable electrical power which may not be available on smaller general aviation airplanes. Radar equipment and its maintenance is considerably more expensive than the passive RF lightning and electric field detectors we wish to develop. The Stormscope, presently the only airborne instrument available for lightning mapping, is inherently inaccurate because it derives distance from signal intensity. Details regarding its factor of two inaccuracy are discussed from a theoretical perspective by L.W. Parker and H.W. Kasemir (Airborne Warning Systems for Natural and Aircraft Initiated Lightning, Air Force Contract F19628-79-C-0161, IEEE Transactions on Electromagnetic Compatibility, Vol. EMC-24, May 1982). The results of actual in flight comparisons between the Stormscope derived lightning position and simultaneous radar echoes which show considerable discrepancies has been reported by B.D. Fisher and N.L. Crabill (Summary of Flight Tests of an Airborne Lightning Locator System and Comparison with Ground-Based Measurements of Precipitation and Turbulence, Proc. of Conf. on Aircraft Safety and Operating Problems, NASA/Langley Research Center, CP-2170, Part I, 1981, pp. 251-277).

The proposed lightning interferometer would be inherently more accurate and reliable than the Stormscope because it works on different principles as outlined briefly later in this report and in detail in our forthcoming Phase II proposal. It was originally developed to study lightning by a member of our team, Professor James Warwick, and his graduate student, Craig Hayenga, and has been proven in multi-station ground installations. The novel approach we have investigated theoretically for single-station use on aircraft would derive distance from the difference between the direct wave and the wave reflected from the earth's surface. Our study shows it would have a range of at least 100 to probably 150 miles. Unlike radar, the longer wave lightning produced RF signals are not attenuated by rain. In addition, the d.c. electric field sensing system we have been developing can pick up increases in electric field intensity near the aircraft before the fields reach lightning intensity. By flying away from such regions the aircraft will minimize the probability of being hit by lightning which it triggers through its presence in high electric fields near developing thunderclouds.

Ideally, for maximum protection and operational flexibility, aircraft should be equipped with both radar and lightning/electric field instrumentation. If radar shows rainfall areas ahead which do not contain lightning, and if the electric field intensity does not build up significantly as the aircraft penetrates the rain areas, an aircraft could proceed with caution. The electric field level that should not be exceeded will be

determined in Phase II. While the heaviest rainshowers by themselves are not dangerous, without the lightning/electric field information, an aircraft might encounter a thunderstorm by flying into heavy rain regions. Alternately, there may be little or no rain in or near thundercloud regions where there would be a lightning and turbulence hazard; such conditions can occur in the dry airmasses of the southwest United States. While radar would give no warning, the proposed instrumentation would detect such potentially dangerous areas.

The objectives of Phase I were (1) to investigate the use of simple corona current instrumentation on aircraft to measure thunderstorm electric fields and (2) to conduct a feasibility study of a single station aircraft lightning interferometer to detect the occurrence and position of lightning. Both of these techniques have the common purpose of providing warning to aircraft crews when they are approaching potentially hazardous clouds and thunderstorms. The electric field measurement has the advantage of detecting electrified clouds which may not be producing lightning flashes but are nevertheless dangerous because an aircraft can trigger lightning; however this is a relatively short range system (on the order of 10 to 20 miles). The interferometer, which responds to RF pulses from lightning, has the advantage of long range detection (more than 100 miles) and can map the position of lightning flashes in a manner similar to the way radar maps areas of rain. Thus the systems complement each other.

During Phase I initial research on corona instrumentation involved laboratory measurements with points of varying sharpness and high ohm resistors which minimize effects due to ventilation. It was determined that at aircraft velocities corona current measurements could be made independent of wind velocity as discussed in the original proposal.

Subsequently, aircraft corona current and radioactive probe vertical electric field measurements were obtained near thunderstorms in New Mexico and North Carolina. It was found that the corona threshold characteristic--the minimum potential required for points to go into corona which was about 3 to 4 kV--limited this system from activating until the aircraft was close to the electrified clouds, while the radioactive probe instrumentation could detect rising electric fields above fair-weather values at distances of 15 miles or greater. Other limitations of the corona instrumentation (e.g., point erosion) were identified and investigated. On the other hand, the radioactive probe systems proved to be quite reliable and by positioning the probes close to the wing surface we found that these systems functioned in thin clouds. By introducing impact shields in front of the electrodes this type of instrumentation should operate reliably in clouds. Therefore, in Phase II we plan to develop radioactive probe instrumentation rather than corona points for the d.c. electric field sensing system. As discussed in our Phase I proposal, such systems are relatively simple to install (require no significant structural modification to the aircraft), have no moving parts, are light and have minimal power requirements.

The Lightning Interferometer study was restricted because funds were not available in Phase I to build instruments. This technique was investigated both in laboratory experiments with a digital oscilloscope/waveform analyzer and with a computer feasibility and literature study conducted by Professor Arthur Uhler. The results of this analysis show that the ocean is a

particularly favorable regime for the proposed innovative single-station ranging method which makes use of the reflection of the radio waves from the sea surface. While the method appears certain over water, it probably will also work well over most land areas except possibly over mountainous terrain. A summary of the study prepared by Dr. Uhlir is contained in Section C. An important conclusion was that existing television and VCR technology could be utilized in the development and ultimate construction of the interferometer. In addition, state-of-the-art and emerging digital components will provide exactly the sort of signal processing required. Because of favorable theoretical considerations, availability of fast digital signal processing components, and the demonstrated usefulness of lightning mapping equipment for storm avoidance, we recommend developing a working model of the aircraft lightning interferometer through a program to be described in our Phase II proposal.

B. ELECTRIC FIELD MEASUREMENTS

-- Laboratory Studies of Corona Instrumentation.

Experiments were conducted in the laboratory and on the aircraft to examine the relationship of corona currents to electric field intensity as a function of wind velocities, and variable input resistance. Input resistors with values ranging from 10^9 to 10^{11} ohms were tested.

Figure 1 illustrates the linear characteristic of the corona current to electric field intensity using a 5×10^9 ohm resistor; the ion cloud resistance is negligible at high velocities (aircraft velocities) so that most of the resistance is from the known input resistor (dashed line). This demonstrates that corona currents can be made insensitive to wind velocity which was an objective of the Phase I program.

Figure 2, derived from the data of Fig. 1, shows that the resistance of the ion cloud decreases with wind speed so that for aircraft velocities greater than about 140 mph the total resistance would be near the theoretical limit of 5×10^9 ohms due to the input resistor. Experiments showed that ion cloud resistances at aircraft velocities were less than 5×10^9 ohms, or 10% of the total resistance.

Figure 3 depicts the difference between corona currents from sharp (1 u) and dull (40 u) points in positive and negative electric fields. The V^+ notation indicates positive charge on a screen over the point which causes negative charge to be emitted from the point. Note that negative corona current onset occurs at lower voltages than for positive corona and that the sharper point produces more current for the same potential. A limitation of using sharp points, however, is that these are quickly eroded.

Figure 4 illustrates the corona threshold of about 3 kV required for the points to go into corona and at aircraft velocities with a high ohm resistor the linear relationship of corona current to electric field. This figure combines several sets of aircraft measurements. The separated set of points in the upper right quadrant may be due to changes in point sharpness due to erosion and illustrate the difficulty in precise calibration of corona measurements of electric fields.

A. Reliability Codes	
Standard	Special
<div style="text-align: right;">64</div>	



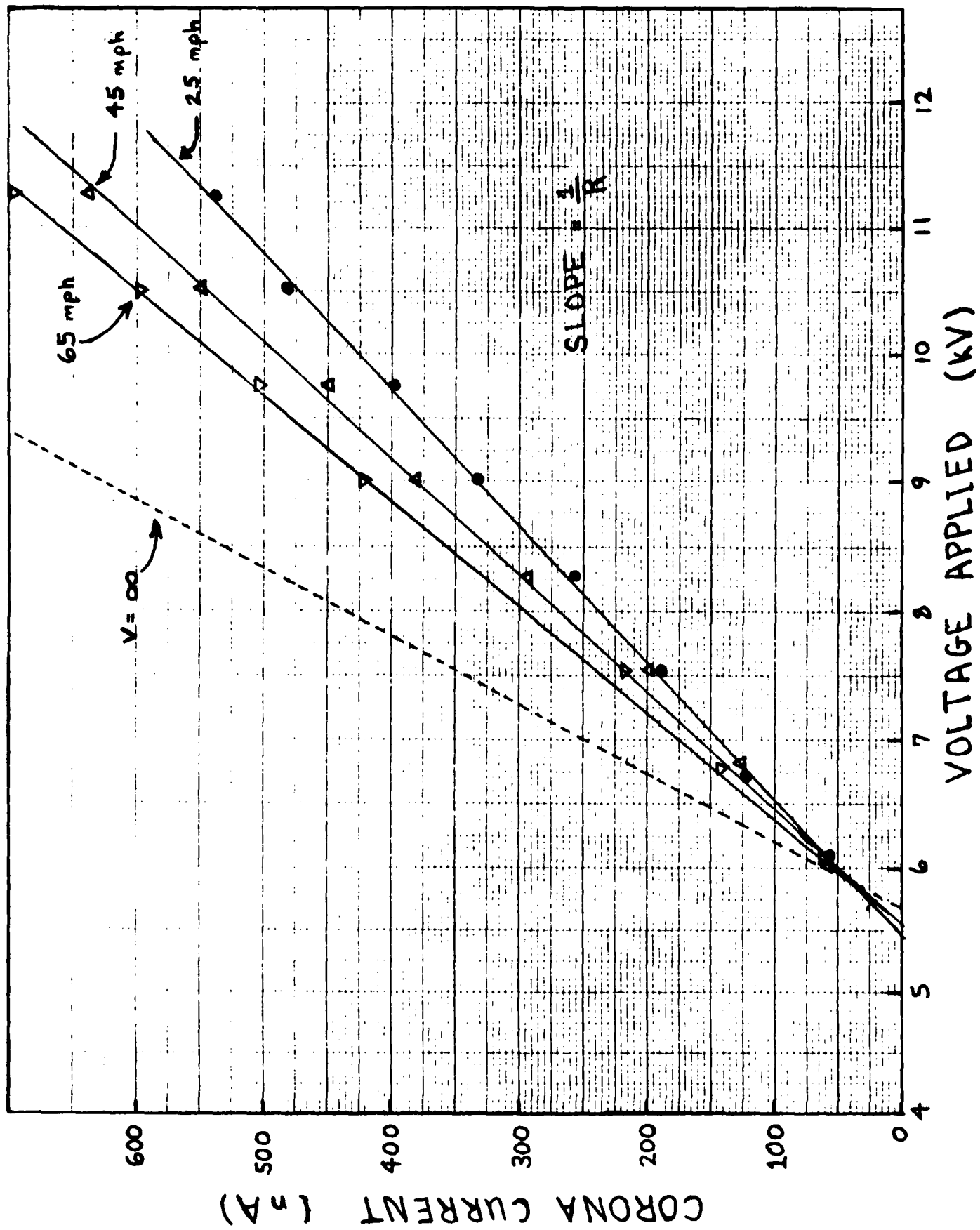


FIG. 1

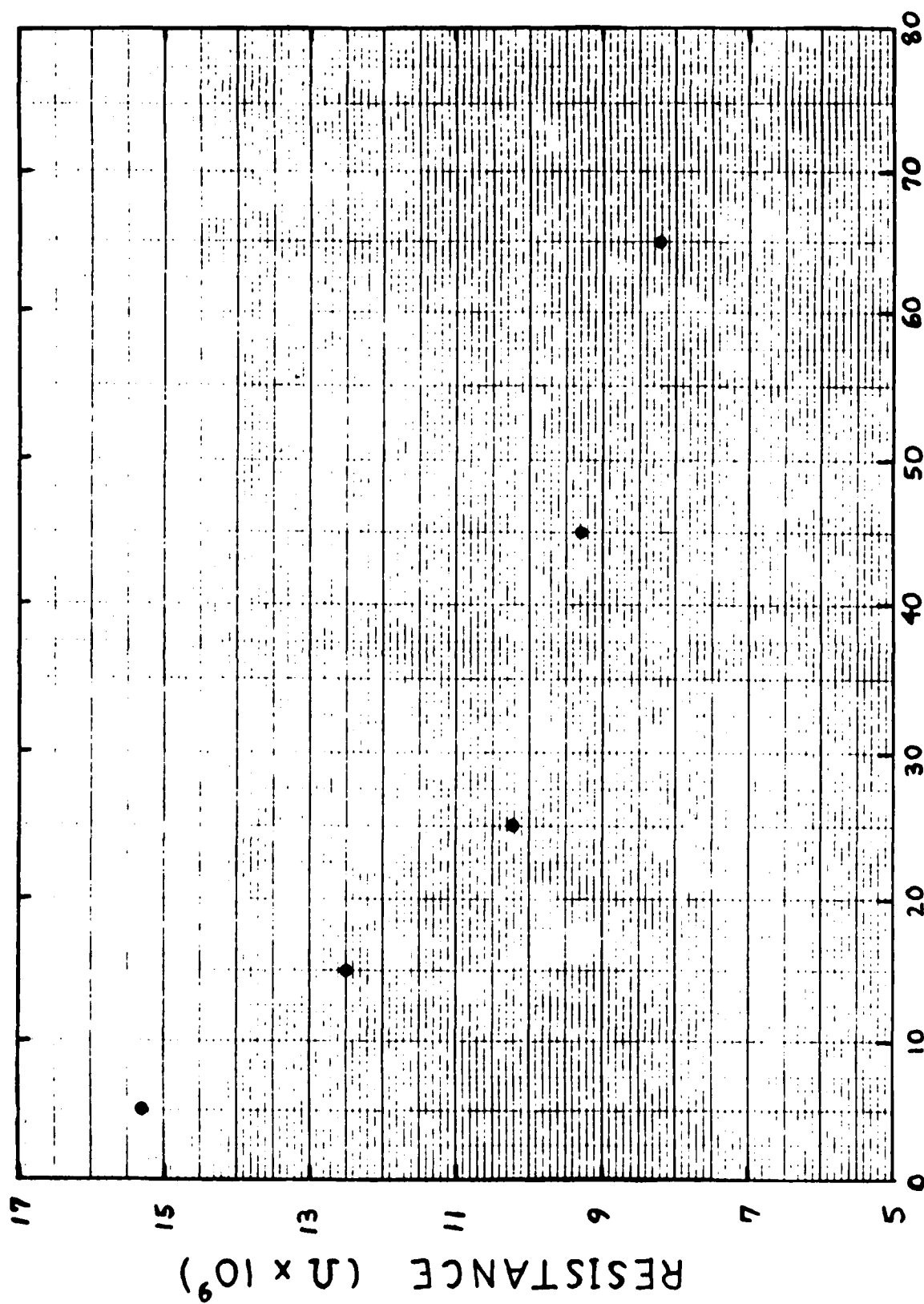


FIG. 2

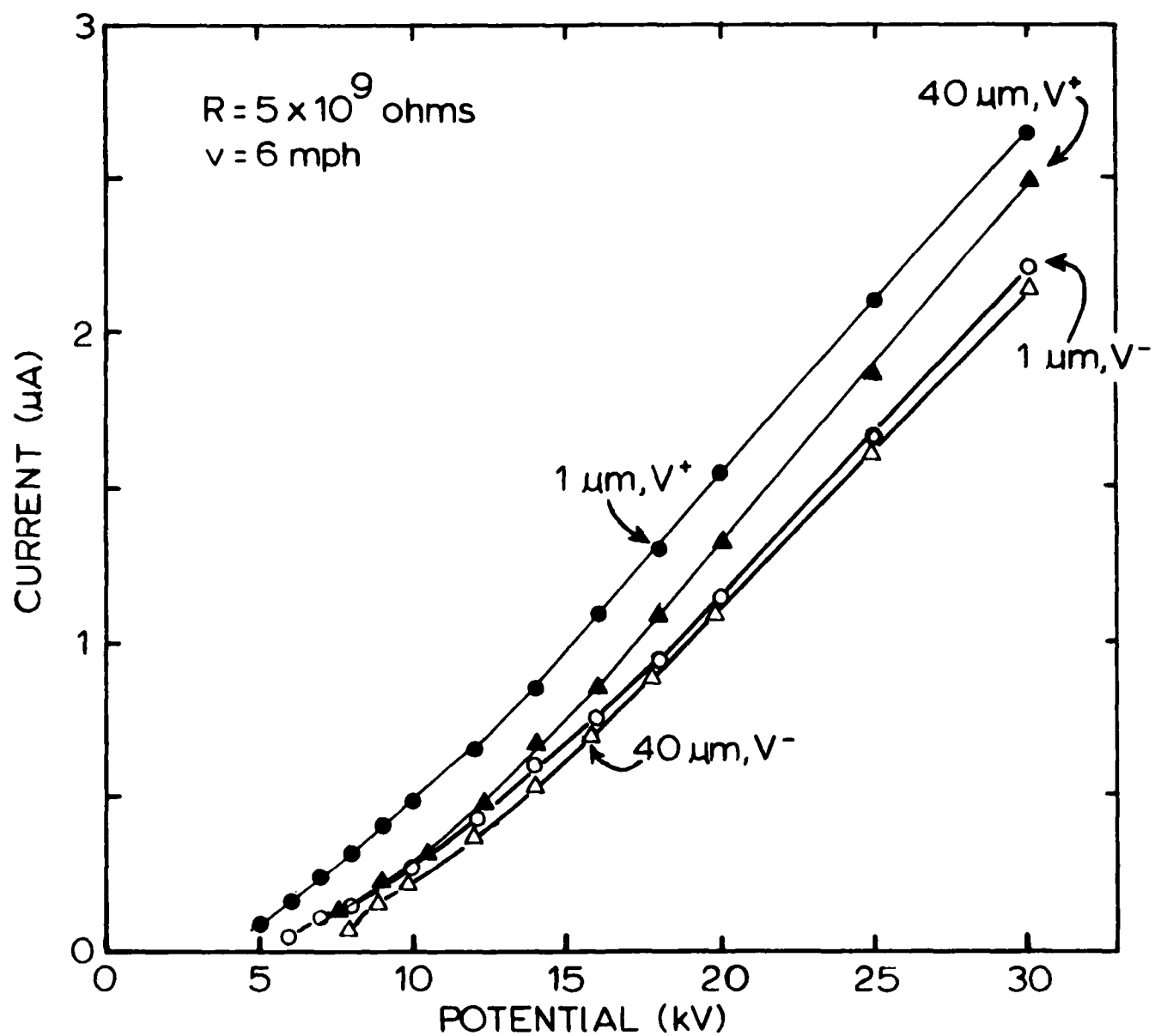
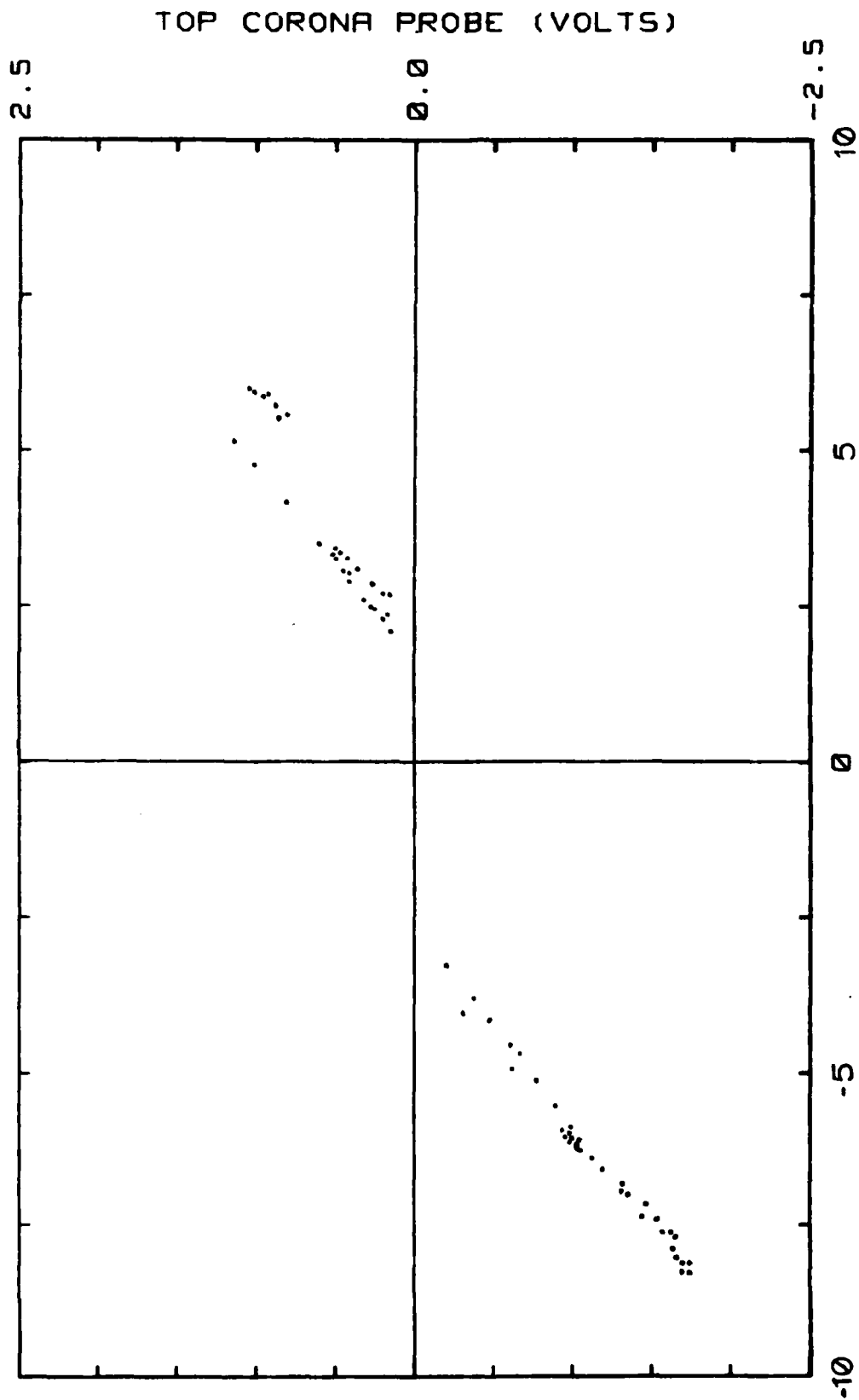


FIG. 3



TOP RADIOACTIVE PROBE (kV)
7-AUG-85 TAPE2; ALL FILES

FIG. 4

-- Testing During Field Programs and Scientific Results.

Initial data were recorded on the TurboBaron aircraft in the vicinity of Langmuir Laboratory at Socorro, New Mexico during August 1985. Socorro is an advantageous place for us to study thunderclouds because they are isolated and frequently do not exceed the Baron's ceiling of 32,000 ft. Thus, it is possible to fly in thunderstorm intensity electric fields over and next to electrified clouds without the danger of flying through thunderstorms. When necessary, in order to observe the effects of droplets and hydrometeors, it is possible to safely penetrate parts of these relatively small well defined clouds. These measurements were made in conjunction with an experiment being conducted by Professors Charles Moore and Bernard Vonnegut who were attempting to test the convective theory of thunderstorm electrification by releasing negative space charge from long wires stretched between mountain peaks. If an inverted dipole resulted (i.e., the opposite of the common condition in which positive charge accumulates near the cloud top), this would indicate that convection carried the negative charge to the cloud top. Passes made under and over the clouds being studied showed clearly that the negative charge was carried upward into the clouds over the mountains and several instances were recorded of negative charge in the cloud tops (see Fig. 5). While these measurements support the convective electrification hypothesis, there were an abnormally low number of thunderstorms at the test site during the summer of 1985 and more cloud top data will be required before firm conclusions are possible. We plan to continue these measurements with Vonnegut and Moore at Socorro during summer 1986 while testing the new instrumentation being developed in this program during Phase II.

The second field period was in January-March 1986 in the region of North Carolina and adjacent coastal waters as part of PROJECT GALE. The objective of this research was to determine if there are naturally occurring "inverted" thunderclouds by observing if the electrified clouds in the winter Atlantic coastal storms, which frequently produce lightning carrying positive charge to ground (opposite the usual case), have negative charge in their tops. This condition would be similar to the Socorro Experiment except the cloud's polarity would be influenced by natural conditions rather than by the man-made changes in the environment of developing clouds. We found many instances of negative charge in the tops of middle level electrified clouds (20-30,000 ft tops). These findings do not imply that typical higher summer thunderstorms would have inverted dipole structure--but our measurements indicate this is common with lower winter clouds (at least in certain regions).

Why does this occur? This may be a function of the warmer temperatures near cloud top; the upper portions of the storms we studied are in the -10 to -20C level characteristic of the layer of negative charge frequently found near the middle of the larger thunderstorms studied by various investigators in the past. Thus, the temperature range, which would allow mixed phase hydrometeors (ice and water), may account for the negative charge. There are various charging mechanisms (such as riming) which require mixed phase cloud particles. Alternately, it may be that the inverted dipole structure resulted from developing clouds feeding on negative space charge injected into the lower atmosphere in the vicinity of larger normal polarity thunderstorms. Many of the middle level clouds we observed to have negative charge in their

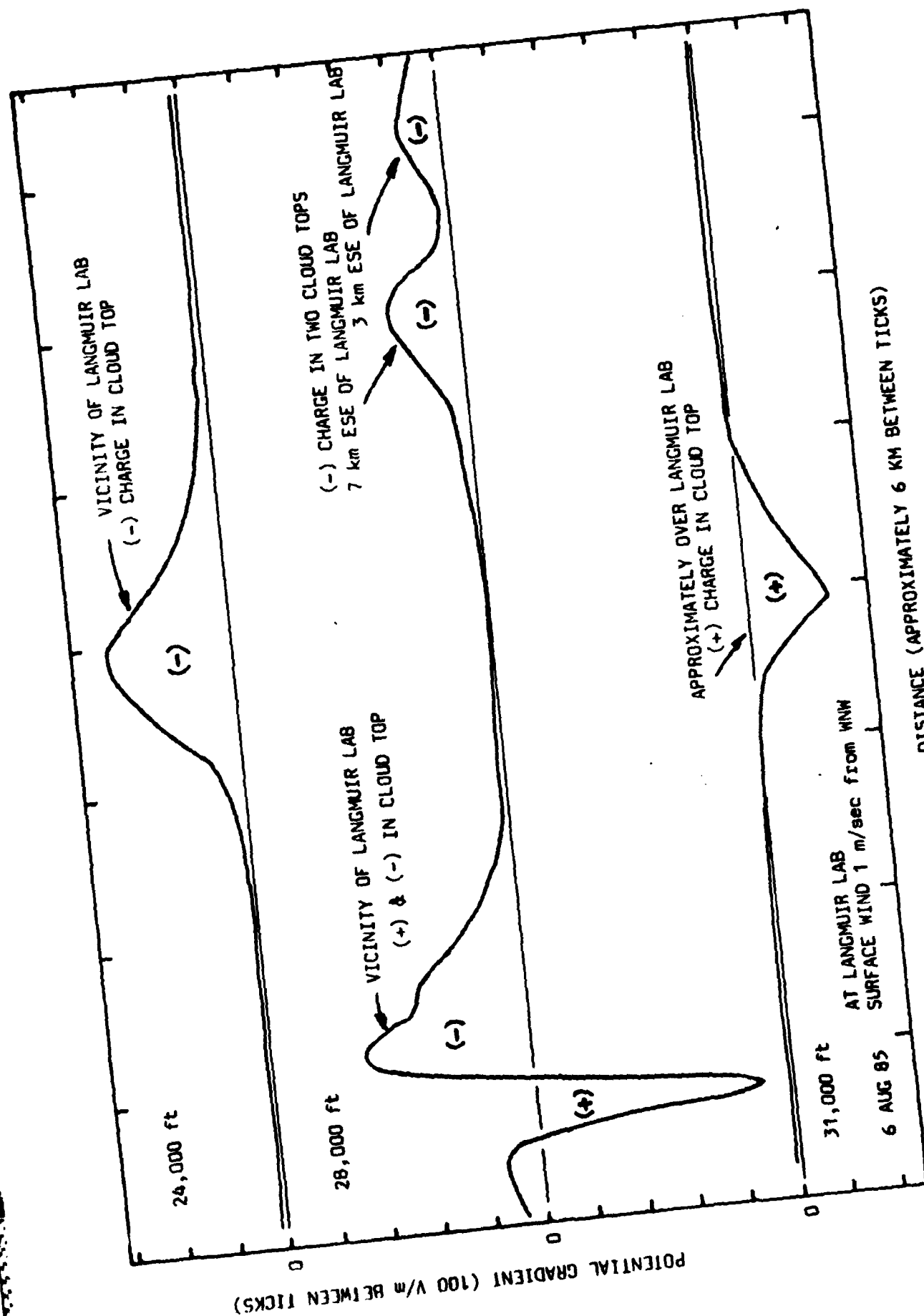


FIG. 5

upper portions were close to large thunderstorms that we could not overfly. Downdrafts from the large storms could have carried negative charge from screening layers to the subcloud region of the smaller electrified clouds that were flown over. This possibility has been suggested by Professor Vonnegut in the past (Annual Meeting of AGU, San Francisco, Dec. 1985). The Socorro and North Carolina measurements mentioned above will be reported in planned publications.

-- Discussion of Electric Field Data

It was found that while the corona current measurements gave a rough indication of electric field intensity they had some sources of error and limitations as follows:

1. Erosion of the tips which changed their sharpness affected the corona threshold. This also changed the current as a function of electric field intensity making calibration uncertain. This problem was partially overcome by using 10 cm long thin wires instead of sharp needles so that erosion did not change the tip radius and to provide essentially an unlimited number of points since the thin wire itself goes into corona along its length. This, however, reduced the sensitivity of the system.

2. The difference in corona threshold between positive and negative potentials was more than anticipated and caused the negative point to go into corona significantly earlier than the positive one which contributed to uncertainty in calibration. This affect was aggravated by the aircraft charge produced by the engines' exhaust and impaction of particles on the airframe. Because the positive and negative corona thresholds are different, it is not possible to completely balance out affects due to aircraft charge on the differential sensor array as with the radioactive probe systems. The affects of aircraft charge can be minimized by placing the points in the same empirically determined equipotential surface above and below the wing, but this is not a simple process and would be impracticable for commercial application. An attempt was made to decouple the corona points from the aircraft ground reference by connecting the points together and measuring the current passing between them. Thus, when one point goes into corona it would immediately force the other into corona. However, to isolate and measure microamp signals from electrodes, which at times vary by several kV from aircraft ground, poses a complex problem involving floating the electronics. An optically isolated current meter was developed and tested and will be used on the Baron in future thunderstorm research. In sum, we concluded that the corona technique which has been used successfully for thunderstorm electric field measurements from uncharged free balloons where the ground potential is well defined (A. Few, Rice University) would not be easily adopted for routine operational use on non-research aircraft.

3. A major problem which became apparent was that with electric field intensities of several thousand volts per meter required before corona currents occur, it generally was necessary for the aircraft to be quite close to the clouds (within a mile or two) before the system activated. Also, fast electric field changes caused by lightning (temporary reduction of electric field intensity) sometimes extinguished corona currents until the fields built up again to the corona threshold. This caused the corona electric field

records to be erratic and difficult to interpret compared to the relatively smooth radioactive probe system records which show the lightning signatures clearly superimposed on the background d.c. electric field level. In fact, one reason we recommend the radioactive probe system is because the variation in magnitude and frequency of such lightning signatures provides excellent information regarding the proximity of the aircraft to thunderclouds. Figure 6 illustrates the increase in d.c. electric field when the aircraft is about 15 miles away from a thundercloud with lightning superimposed on the trace starting at considerably greater distance. These lightning signatures should not be confused with fraction-of-a-second RF type sferics signals; they are quasi-dc variations arising from the redistribution of space charge in the cloud following lightning discharges. A pilot looking at such a display or a meter showing the integrated area of lightning signatures and its rate of change would know when a dangerous region was being approached. The record ends on the right hand side when the aircraft had to turn away because of increasing turbulence and the close proximity of lightning which could be seen because it was night.

Through comparison between simultaneous electric field records made with corona point and radioactive probe systems it became clear that the latter was the system of choice. The original reason for investigating the use of corona currents for electric field measurements was that impact charging by cloud particles saturated the high impedance radioactive probe systems while this was not a problem with low impedance corona systems. However, we found that by locating the electrodes within a few cm of the wing, not only could the dynamic range of the electronics be extended from fair-weather to thunderstorm intensities but the systems worked in thin clouds. Apparently cloud particles were not impacting the electrodes in this position. Thus, by using grounded small cup-shaped shields to house radioactive probes located close to the wing skin it should be possible to measure thunderstorm intensity electric fields within clouds with the same electrometer design that we have been using; these electronics have proven to be highly reliable. The shields would serve the double function of (1) reducing the potential at the radioactive collector so as not to exceed the dynamic range of the electronics and (2) preventing particles from impacting the electrode. The streamlined housing containing the antenna would be about 6 cm high x 6 cm wide x 25 cm long which is about the same size as aircraft flap hinge fairings.

Figure 7 shows the electric field sensors at the Baron's left wingtip. The long vertical mast has one set of corona points without resistors at its tips. The middle length L shaped antennas have a second set of corona points at the rear of the horizontal electrodes which contain high ohm resistors. The short antenna has radioactive probes bent close to the wing to reduce potentials.

A second radioactive probe array on the right wingtip is seen in Fig. 8. By operating two independent systems which track each other, data reliability is insured; the systems would not give identical results if one or the other was unbalanced relative to aircraft charge. The two Gerdien tubes for (+) and (-) conductivity are seen below the wing. The vertical mast at the wingtip is for turbulence measurements and was not used in the work reported here.

MILES TO T.S.

21	19	15	12	9	6	3	0
2032	2032	2032	2034	2034	2034	2034	2034

2032

2034

2036

2038

2040

2042

2044

2046

2048

2050

2052

2054

2056

2058

2060

2062

2064

2066

2068

2070

2072

2074

2076

2078

2080

2082

2084

2086

2088

2090

2092

2094

2096

2098

2100

2102

2104

2106

2108

2110

2112

2114

2116

2118

2120

2122

2124

2126

2128

2130

2132

2134

2136

2138

2140

2142

2144

2146

2148

2150

2152

2154

2156

2158

2160

2162

2164

2166

2168

2170

2172

2174

2176

2178

2180

2182

2184

2186

2188

2190

2192

2194

2196

2198

2200

2202

2204

2206

2208

2210

2212

2214

2216

2218

2220

2222

2224

2226

2228

2230

2232

2234

2236

2238

2240

2242

2244

2246

2248

2250

2252

2254

2256

2258

2260

2262

2264

2266

2268

2270

2272

2274

2276

2278

2280

2282

2284

2286

2288

2290

2292

2294

2296

2298

2300

2302

2304

2306

2308

2310

2312

2314

2316

2318

2320

2322

2324

2326

2328

2330

2332

2334

2336

2338

2340

2342

2344

2346

2348

2350

2352

2354

2356

2358

2360

2362

2364

2366

2368

2370

2372

2374

2376

2378

2380

2382

2384

2386

2388

2390

2392

2394

2396

2398

2400

2402

2404

2406

2408

2410

2412

2414

2416

2418

2420

2422

2424

2426

2428

2430

2432

2434

2436

2438

2440

2442

2444

2446

2448

2450

2452

2454

2456

2458

2460

2462

2464

2466

2468

2470

2472

2474

2476

2478

2480

2482

2484

2486

2488

2490

2492

2494

2496

2498

2500

2502

2504

2506

2508

2510

2512

2514

2516

2518

2520

2522

2524

2526

2528

2530

2532

2534

2536

2538

2540

2542

2544

2546

2548

2550

2552

2554

2556

2558

2560

2562

2564

2566

2568

2570

2572

2574

2576

2578

2580

2582

2584

2586

2588

2590

2592

2594

2596

2598

2600

2602

2604

2606

2608

2610

2612

2614

2616

2618

2620

2622

2624

2626

2628

2630

2632

2634

2636

2638

2640

2642

2644

2646

2648

2650

2652

2654

2656

2658

2660

2662

2664

2666

2668

2670

2672

2674

2676

2678

2680

2682

2684

2686

2688

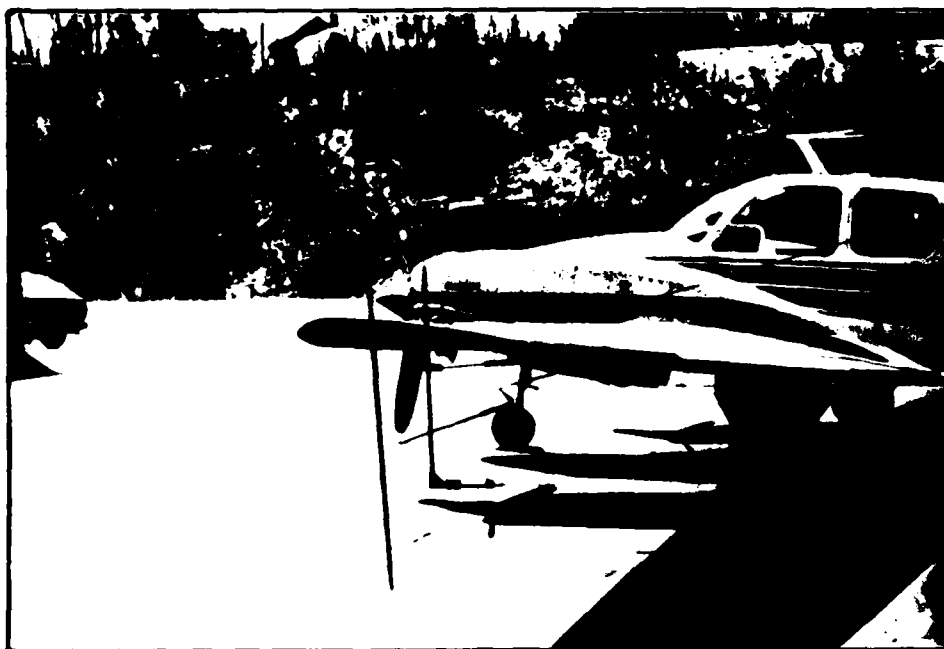


FIG. 7



FIG. 8

C. LIGHTNING INTERFEROMETER FEASIBILITY STUDY

DESIGN OF LIGHTNING LOCATION SYSTEM

Introduction

The objective of this study is to develop the specifications for electronic circuitry to determine the range of cloud discharges by radio observations from an aircraft in flight over the ocean. The principle of operation is the interference between radio waves travelling directly and by reflection from the sea.

The completion of the lightning location by determination of the azimuth is a relatively simple matter, for which satisfactory methods have long been available. For example, a crossed-loop scheme would provide azimuthal resolution useful for storm avoidance. However, once interferometric signal-processing is adopted for ranging, it may be considered also as a means of providing improved azimuthal accuracy.

The features of the ranging technique will first be described qualitatively. To a great extent, the qualitative description relies upon quantitative calculations that had to be made first, although they are here presented later.

Geometric factors enter first of all in the time difference that is the basis for ranging. They are also involved, along with electromagnetic factors, in the relative strength of the direct and reflected signals. In turn, the time difference and the signal strength determine the specifications for the electronic system.

General Features of the Method

The sea is a remarkably good mirror for radio waves. The dielectric constant of water is 80 at these frequencies (in contrast to a value of 1.8 at optical frequencies) and is mainly responsible for the remarkable reflectivity. The conductivity of sea water further improves the reflectivity, but that improvement would not be necessary for the method to be applicable over large bodies of fresh water.

The intrinsic reflectivity of land is generally fairly good and the method does not require the extraordinarily high reflectivity of water. The main limitation is roughness of terrain, which can greatly exceed that of the ocean. Also, it is necessary to know the altitude of the reflecting surface, which is no problem when the surface is the ocean.

Historically, the specular reflection of radio waves from the sea has been more of a hindrance than a help to communication in naval aviation. The interference of direct and reflected waves causes multipath fading in conventional narrow-band radiotelephone or radiotelegraph

systems. The problem is serious enough in ship-to-air communication, but is so marked in air-to-air communication to be called "radio holes."

We intend to use this heretofore troublesome interference effect for lightning ranging. To do so, we must receive over a wide-enough frequency band to encompass destructive and constructive interference several times. The bandwidths that calculations show to be necessary are not especially demanding upon modern electronics technology, being similar to those used in television receivers.

The reflectivity of sea water is always lower for polarization with a vertical electric field than for horizontal polarization. Were it not for the conductivity provided by its salt content, the reflection for vertical polarization would go down to zero at an angle of incidence (the Brewster angle) within our range of interest. These predictions of electromagnetic theory were validated experimentally for the design of naval aviation radio, for which vertical polarization is therefore preferred, to reduce the severity of multipath effects.

Conversely, horizontal polarization seems preferable for a lightning ranging system based on reflection. Further, horizontal polarization should favor the more frequent intra-cloud discharges, which we would prefer to receive, relative to the less-frequent cloud-to-sea discharges. Another advantage of horizontal polarization is discrimination against vertically polarized communications signals.

The interference-fringe concept of lightning ranging was outlined in the original proposal under the approximation of a flat ocean. Corrections for the spherical shape of the earth are significant at long ranges. Because of the favorably high reflectivity of the sea, we can expect to achieve ranges where the curvature will affect the calibration. However, either level of approximation shows that the longer the range, the shorter the time difference. This relationship is in the opposite direction of the range-time relationship in radar. The time difference in nanoseconds will be substantially equal to the difference in the lengths of the direct and reflected paths, in feet, because the refractive index of air is not much different from that of free space (where one foot corresponds to 1.02 nanoseconds).

Nevertheless, the slight decrease with altitude of the refractive index of the atmosphere does have a significant effect. It causes the radio waves to travel in curved paths while in the atmosphere. This effect is approximately allowed for by using a fictitious radius for the earth: usually taken to be $4/3$ of the actual radius. One then can represent radio rays by straight lines in geometric calculations.

Concern about multipath effects from the ionosphere

raised the possibility of having to work at high enough frequencies to avoid such reflections. The quantitative calculations allay this concern. The time delays of the ionospheric reflection will be longer than the time delays of the reflection from the sea in all cases of interest. Thus, the ionosphere does not place much of a constraint upon the choice of frequency. The true earth radius is used in the ionospheric delay calculations because most of the path lies outside of the refractive index gradient of the lower atmosphere.

The reflectivity of the sea is extremely high for all radio frequencies under consideration. But frequency is very much a factor in assessing the effect of ocean waves. The lower the frequency, the longer the radio wavelength and the less the effect of sea waves. However, the impairment of reflectivity is less than one might expect from the comparison of wave height to radio wavelength. When the grazing angle is small, the effect of sea waves on the reflectivity is greatly diminished. Small grazing angles prevail for the longest ranges. (The grazing angle is the angle between the ray and the plane of the reflecting surface; that is, the tangent plane if the surface is curved. In other words, the grazing angle is the complement of the angle of incidence measured between the ray and the normal to the surface.)

Signal processing to determine the time difference seems simpler in concept when the original signal spectrum does not vary wildly over the band that is measured. The desirable condition is favored by keeping the relative bandwidth small. A 6 MHz band around 60 MHz is an example. The center frequency is not critical and it would not be costly to provide selectable frequencies to avoid particularly strong man-made interference.

A smoothly-varying signal spectrum can be undone by nonuniform response of the antenna. Making the center frequency much larger than the bandwidth eases the antenna design problem, while offering a choice of frequencies increases the problem. It would be possible to calibrate the system with reference to a standard spark. The ability to store such a calibration and to apply it as a correction is one of the advantages of digital processing.

The convex sphericity of the earth's surface causes the reflected wave to diverge and thereby be reduced in intensity. This effect is largest for small grazing angles; that is, for the longest ranges. The relative intensity of the reflected wave is also slightly reduced because of its longer length compared to the direct path; this effect has been included in the calculations but is not very important in cases of interest.

The advantages of digital signal processing seem compelling after review of the literature on time-delay extraction. This literature has been inspired largely for underwater sound applications. Recent progress in digital electronics makes it practical to apply the same

methods to the microsecond time scale of the radio multipath situation.

A critical component in the contemplated system is the analog-to-digital converter (ADC). Because lightning signals are quite strong, the roundoff error of the ADC may be the principle source of "noise." At the same time, the ADC must sample fast enough to encompass the needed bandwidth to identify clearly the interference pattern. These requirements combine to determine the feasibility (confirmed by an instrument used in this investigation) and cost (not negligible but expected to decrease) of using an ADC to permit digital signal processing.

The receiver specifications that have been developed have much in common with those of a conventional television receiver. This fact is expected to lead to significant economies in both prototype and production phases through use of components that are already in mass production. Some additions and modifications are needed, of course. Protection against gross electrical overloads is important. Compression of strong but useful signals is expected to ease the requirements on the ADC, but must not introduce irreversible distortion. The compression would supplant the slower-acting automatic gain control used in television receivers.

Propagation Calculations

The propagation calculations have been combined in a computer program given in Appendix A. The basis for the several subcalculations will be given in the sections that follow, along with sample graphs of results, to substantiate the quantitative basis for the system specifications. Then the signal processing and electronic design discussion will follow.

With the exception of π and λ , the symbols used in this discussion are defined to be the same as in the symbol table of Appendix A.

Path Differences

The fundamental indicator of the lightning range is to be the time difference between the directly transmitted electromagnetic radiation and the radiation that is reflected from the sea. The time difference in nanoseconds is practically equal to the difference in the length of the two paths in feet. The fact that the refractive index of air is slightly greater than unity is of negligible consequence in this relation and the reflection from the sea can be assumed to take place without delay.

The gradient in the refractive index of the atmosphere is of some significance because the ray paths will be curved. The use of an artificial earth radius of $4/3$ of its actual value is conventional and adopted here.

This correction is not critical in this application and the reason can best be explained by contrast to those applications where it is sometimes not accurate enough to assume a 4/3 earth radius. For example, communication by a narrowly focused beam of microwaves or light may require careful aiming to cause the strongest part of the transmitted beam to be intercepted by the receiving aperture. If atmospheric changes cause a different degree of bending, the signal could be lost entirely. Lightning emits radio waves strongly in all directions, so that the only effect of an aberrant refractive-index profile would be a minor error in range estimate.

The geometry of the path difference calculation is shown in Fig. 1, from the first report. The main check on the correctness of the calculation comes from the approximate formula

$$\text{Approximate Path Difference} = 2 \cdot H_1 \cdot H_2 / D$$

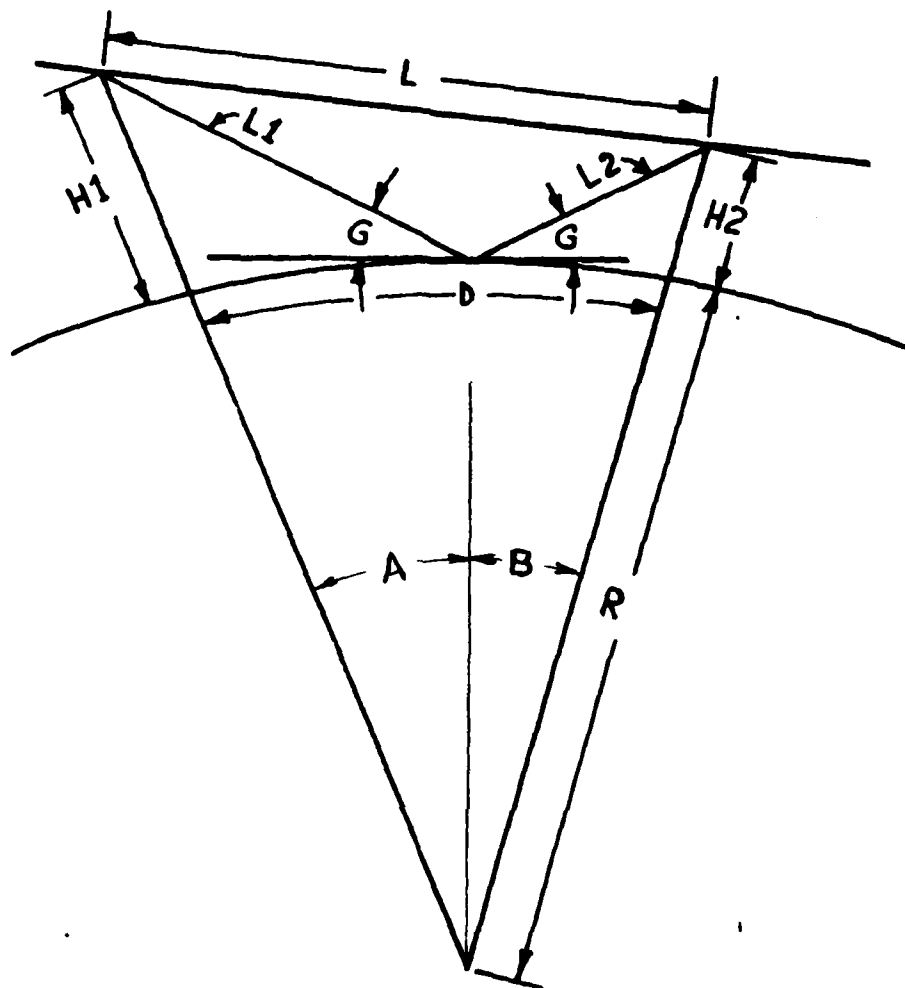
where H_1 and H_2 are the altitudes and D is the range. This formula was used in the proposal. It is based upon a flat earth and therefore becomes inaccurate at long ranges. It uses approximations to the trigonometric functions and for this reason also becomes inaccurate at very short ranges. It is calculated in the program as the variable P9.

The more accurate path difference P0 is calculated in the program of Appendix A in accordance with the geometry shown in Fig. 1, including the use of 4/3 earth radius. Results for P0 are given as the solid curve in Fig. 2 and in Fig. 3, for sample cases. The approximate path difference P9 is also shown as a brokenline and corresponds closely to the more accurate calculation for intermediate ranges of 10 to 100 miles, for these typical altitudes. The more accurate calculation exhibits the phenomenon of a radio horizon, where the path difference vanishes, at ranges of about 300 miles for these examples.

Another path difference of interest is that for the possible competing reflection from the ionosphere. A mirror-like ionosphere at the low height of 150,000 ft would even so have a delay time far longer than the values expected for the sea reflection. (Figures 2 and 3 have been extended upward so that this extreme case can be seen in the upper right-hand corner.) In fact, the ionosphere would not be nearly as sharp or effective a reflector as the sea at the frequencies that will be recommended below.

Reflectivity of Sea Water

The dielectric constant and conductivity of sea water can be regarded as independent of frequency, at least through the ordinary microwave frequencies. This constancy implies, however, a frequency dependence of



$R = 4/3$ earth radius

Fig. 1. Geometry for path difference calculation

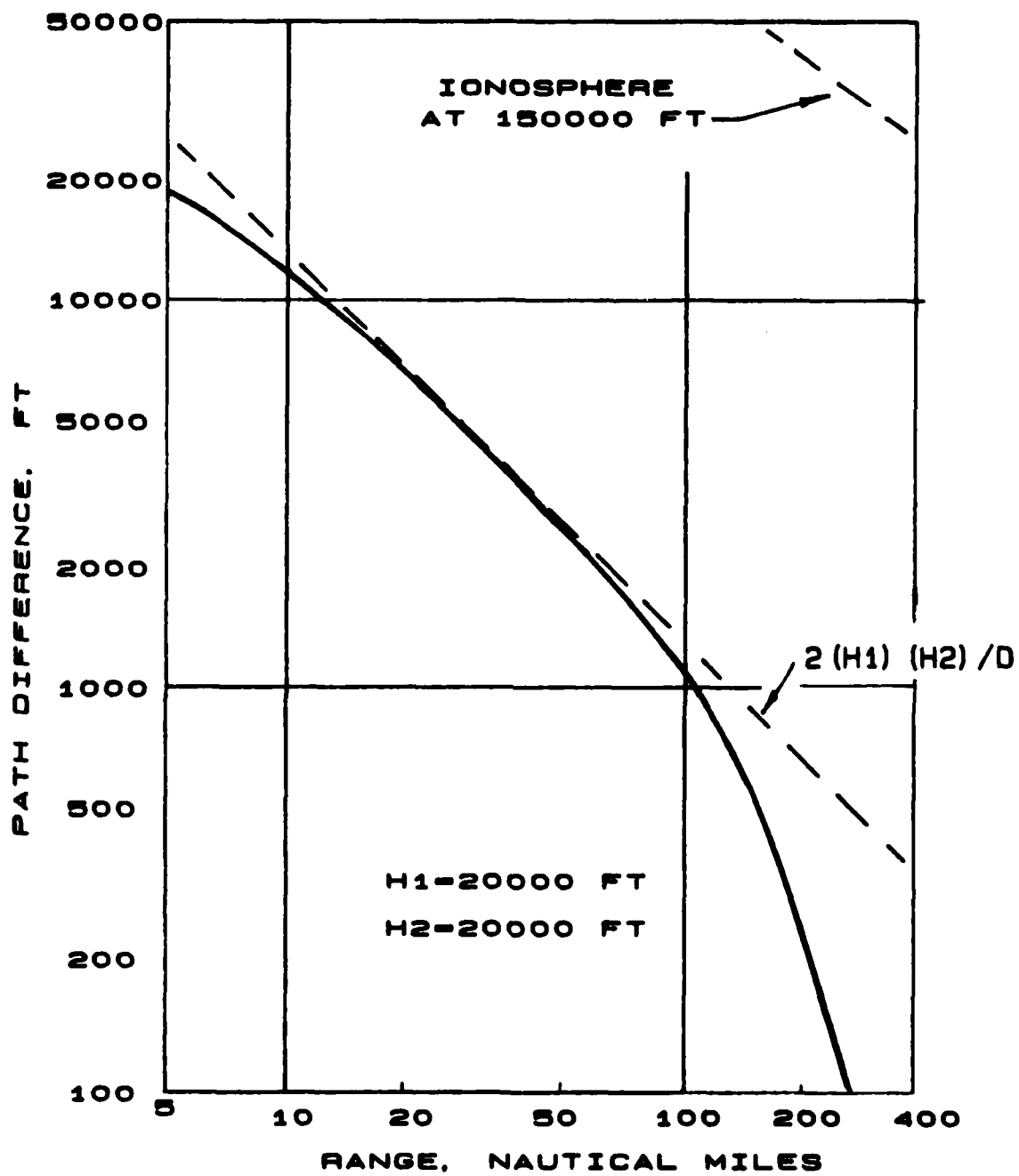


Fig. 2. Path difference for equal altitudes

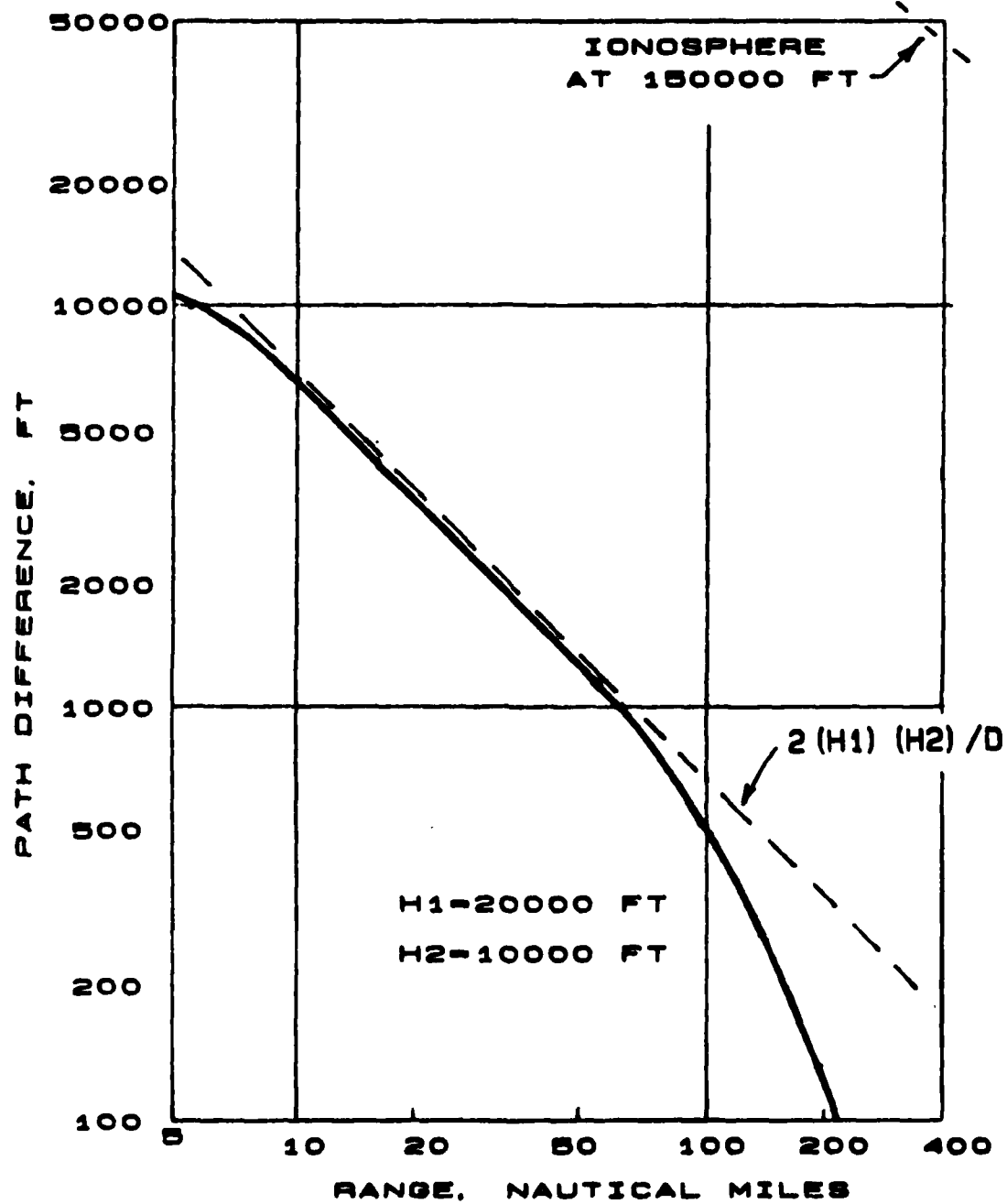


Fig. 3. Path difference for unequal altitudes

reflectivity. The reflectivity also depends upon the grazing angle of the incident ray.

For waves with horizontal electric field polarization, the reflectivity is remarkably high, for all frequencies and angles. At low frequencies, the conductivity of sea water further enhances the reflectivity, an improvement that is not at all necessary for our application. Thus, the reflectivity is also high for fresh water and substantially independent of frequency.

Vertical polarization presents a more complicated situation. The reflectivity decreases as grazing angle increases to approximately the Brewster angle (where the reflectivity would vanish were it not for the conductivity due to the salt content). The lower reflectivity, particularly for the longer ranges, makes vertical polarization seem less desirable than horizontal polarization.

The reflectivities for horizontal and vertical polarization by the routines in the computer program are in complete agreement with published theoretical graphs (e.g., Ref. 1, p93). Furthermore, these theoretical values are well corroborated by experiments at VHF and UHF frequencies (ibid., Chapt. 12). The graphs to be presented here will not be reproductions of the basic reflectivity information; they will incorporate additional factors to be discussed.

Effect of Waves

One expects the sea to be smooth enough for specular reflection when the waves are smaller than the wavelength of the radiation. But the situation is much more favorable than that, for our application. For small grazing angles, the effect of waves is proportionately reduced.

Experimental results on forward scattering of radio or microwaves are surprisingly scarce. A relatively recent and comprehensive survey of the literature is given in Ref. 2. Since then, one interesting experiment was conducted with 3 cm radiation at a fixed grazing angle of 0.5 degrees (Ref. 3). Over a period of several months, the waves rarely caused as much as 8 dB decrease in the strength of the reflection. In considering 60 MHz radio waves of 5 meters wavelength for lightning ranging, one can therefore be optimistic that sea waves will be a tolerable problem, perhaps not even as troublesome as the estimate based on the simple theory used in the program.

The description of waves is itself problematical. It is commonplace to report the peak-to-trough height estimated visually. The rare "rogue wave" rightly feared by the small-boat sailor is of no concern to us and, in fact, root-mean-square height is used the the simple theory of Ref. 4 (pp316-319). Following this reference, the program converts the peak-to-trough wave height W_l in

feet to an rms wave height W in meters. The peak-to-trough height is supposed to be 4.66 times the rms value. Then the expression

$$O2 = e^{-\left(\frac{4\pi W \sin(G)}{\lambda}\right)^2}$$

is taken as the factor by which the reflected power is reduced by the waves. Here λ is the radio wavelength. The presence of the sine of the grazing angle G is most significant. It shows that the waves have the least effect when the grazing angle is small; that is, for the longest ranges.

In contrast to the material reflectivity, the effect of waves is strongly dependent on radio frequency once it becomes a significant factor. The lower frequencies are less affected.

In Fig. 4, a dashed line shows the result of applying the ocean-wave factor to the horizontal polarization reflectivity, after that is corrected for divergence and ratio of path lengths. The effect of waves on vertical polarization may be somewhat different, but not enough in comparison to the approximate nature of the calculation to justify cluttering up the graph with another curve.

Divergence

A spherical reflector functions like a diverging lens and reduces the intensity of the reflection. In radio propagation, this reduction factor is called divergence. It has the largest effect for small grazing angles and is calculated by the approximate formula,

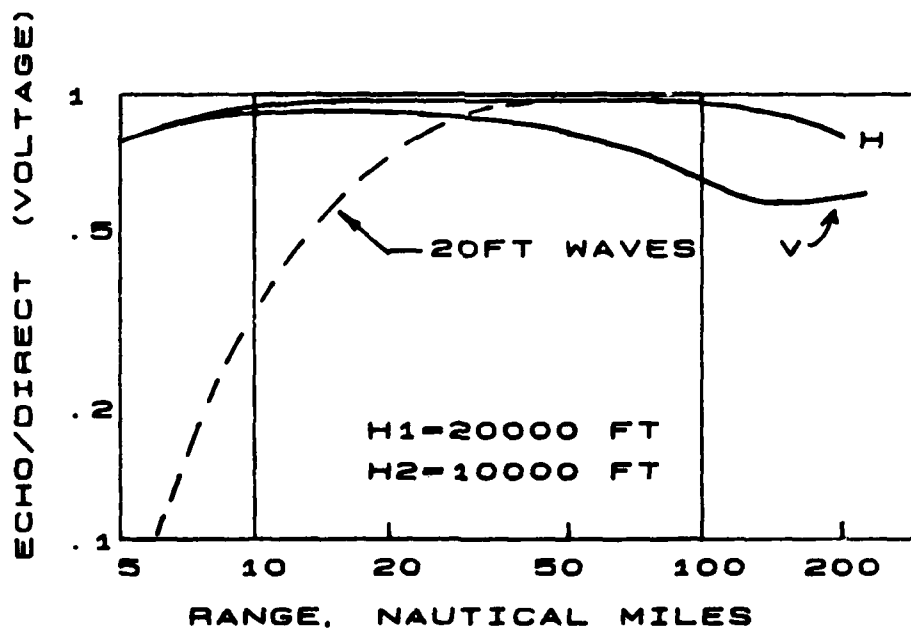
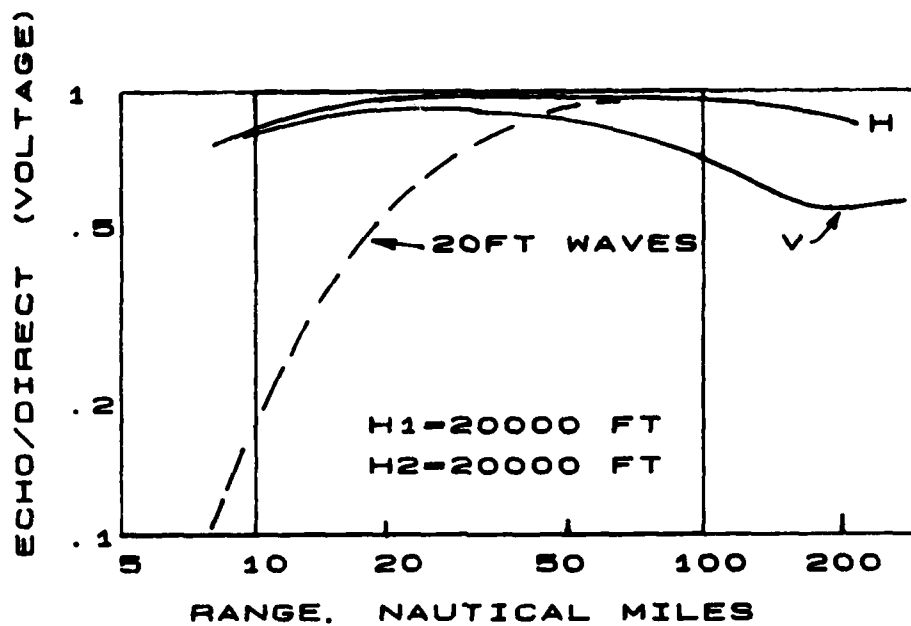
$$D1 = 1/\text{SQR}(1 + 2*R1*R2/(D*R*\text{TAN}(G)))$$

which is Eq 4-133 on page 107 of Ref. 1. The program uses the already calculated values of sine and cosine instead of calculating the tangent.

Relative Magnitude of Reflection

The reflectivity, wave effect and divergence are power ratios. When they are multiplied together, they give the factor by which the reflected wave power is expected to be diminished in comparison to the direct power. The square-root of this power ratio is taken to give the voltage ratio A1. The value of A1 is plotted in Figures 4(a) and 4(b) for the two cases considered in Figs. 2 and 3.

One can see that the reflected signal will be relatively very strong unless one is dealing with a rough sea and ranges that may be shorter than need be considered. The impairment by waves is significant only



Polarization: V=vertical H=horizontal

Fig. 4. Reflection magnitudes for altitude combinations of previous figures.

if they are high over a large area; a few very strong waves will not much reduce the total reflected power.

Antenna Considerations

A simple way to get uniform azimuthal response to horizontal polarization is to use a loop lying in the horizontal plane. A horizontal loop also has an agreeable vertical pattern, in that its gain is largest for the smallest grazing angles, which would be encountered for the most distant lightning. However, alternative antenna designs, such as combinations of horizontal monopoles or dipoles, could probably be arranged to give adequate azimuthal coverage for the ranging function if there were aerodynamic reasons for doing so.

Placement of the ranging antenna underneath the aircraft seems natural and would discriminate against signals reflected from the ionosphere. We have, of course, argued already that such signals should not present much of a problem.

The azimuth determination does not depend upon reflection from the sea, so it could utilize horizontal or vertical polarization. Aerodynamically acceptable antennas at the extremes of the aircraft could be made for either horizontal or vertical polarization, for the interferometric determination of azimuth. In this determination, multipath effects should not cause difficulty, because the signals received by each of the several antennas would have the same echo component.

Signal Characteristics and Processing

From Figs. 2 and 3 one can see that a useful lightning-ranging instrument should be able to deal with path time differences in the range of 0.5 to 10 microseconds (path differences of 500 to 10000 feet). Later increases in bandwidth and processing capability should be able to extend the range to 150 miles or more by evaluating path differences as short as 0.2 microsecond.

The sea is an excellent reflector at all frequencies under consideration. However, the spectrum of the signal produced by lightning is not flat. The signal is strongest at low radio frequencies and decreases (for equal bandwidth) as frequency is increased. The spectrum will be relatively more constant over a specified bandwidth, the higher the frequency. It is easier to make a suitable antenna, the higher the frequency (i.e., when the relative bandwidth is smaller).

A reasonably flat signal spectrum is needed because we have no way of knowing exactly the signal originally radiated from the lightning discharge. If the intrinsic spectrum can be depended upon to be smooth, one

can accurately estimate the path difference from the ripples it introduces into the spectrum. Suppose, for example, that a 6 MHz band centered at 60 MHz is received. The relative bandwidth thus would be 10 per cent. If the signal power varies as $1/f$, the spectrum would look like Fig. 5a in the absence of a reflection. With an echo time of 5 microseconds, the spectrum would look like Fig. 5b; an echo time of 0.5 microseconds would give a received spectrum like Fig. 5c. The spacing of the ripples in frequency obviously permits the 5 microsecond time to be determined accurately and unequivocally. A reasonable observer could also be sure enough about the 0.5 microsecond time difference. But it is apparent that convincing evaluation of a 0.2 microsecond time difference would call for a more sophisticated analysis or a wider bandwidth.

The autocorrelation function and the power spectrum are Fourier transform pairs, so that they should contain equivalent information. But there are important differences in the way they contain this information.

The autocorrelation function has a very strong ability to smooth-over irregularities in the signal. Our experiments with the digital oscilloscope, described below, showed that this smoothing indeed results in a sharply-defined low-noise autocorrelation function, in spite of extraneous features in the raw signal.

Possibly the slight waviness in the autocorrelation function could be analyzed to extract the time delay. But it would be an unfamiliar sort of analysis; there is little experience to suggest methods of dealing with such a subtle function, even granting its high signal-to-noise ratio.

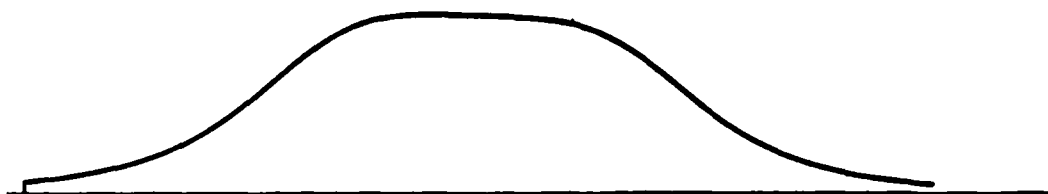
The spectrum, on the other hand, establishes a better distinction between the echo and the extraneous features, so that the latter can be filtered out.

Thus, processing involving spectrum calculations seems desirable and conversion of the signal to digital form seems to be the surest way to accomplish the processing. Once the price of analog-to-digital conversion is paid, important additional benefits can be realized through the versatility of digital processing.

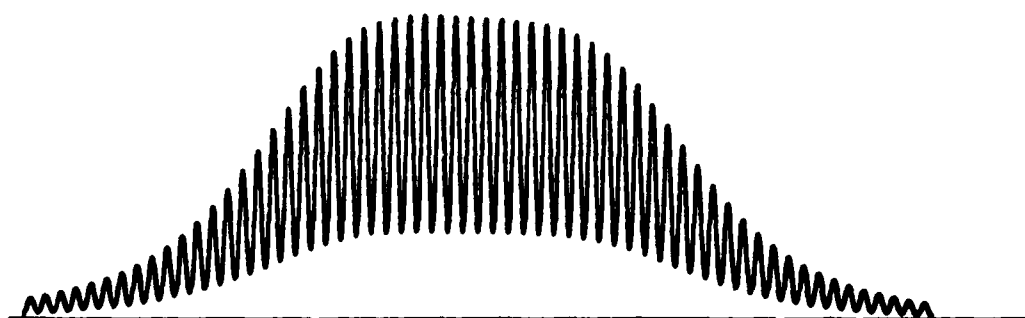
An attractive way of extracting the time delay from just such signals as we expect has been given the name "cepstrum" (from "spectrum" partly turned around). After the spectrum is computed, one takes its logarithm (a quick and simple operation) and then another Fourier transform is taken. Echoes stand out as sharp peaks in the second transform, provided that the signal-to-noise ratio of the original signal is high enough. Just how high will shortly be considered.

First, however, yet another logarithmic operation will be mentioned. It was suggested in the proposal that an analog logarithmic operation on the incoming signal would be advantageous in reducing the dynamic range that subsequent stages would have to accommodate. Published

(a)



(b)



(c)

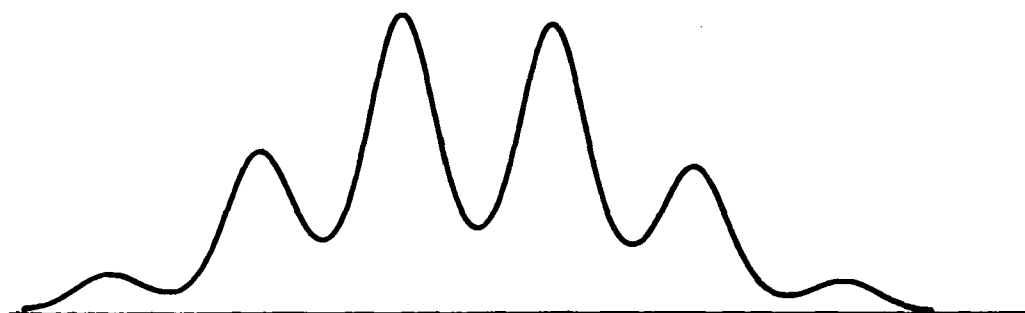


Fig. 5. Band-limited response to $1/f$ spectrum

(a) no echo

(b) 5 microsecond path difference (5000 ft)

(c) 0.5 microsecond path difference (500 ft)

numerical simulations of time-delay extraction do not consider this option. There is little theoretical guidance for this approach. However, we learned from the instrument manufacturer's supervising engineer that the digital oscilloscope plug-in that we found agreeable to work with had just such an input circuit. The compression scheme works well. This analog compression before conversion to digital form does not supplant the subsequent logarithmic operation in the frequency domain in the calculation of the cepstrum; it eases the resolution demands on the ADC.

The signal-to-noise requirements for extracting time delays by cepstrum processing have been analyzed by computer simulation under a variety of assumptions. Numerical simulations reported in Refs. 5-8 indicate that good results are possible down to an SNR of 0 dB or even lower when suitable windows (filters) are used for the characteristics of the signal and noise. In the choice of examples for simulation, the authors of all of the publications that we have examined choose cases that conform to the principle that the bandwidth should be at least several times the reciprocal of the time delay, as one would expect from Fig. 5.

There is evidence in a related situation to show that the results, interpreted as expressing the needed SNR, are not very different for a variety of algorithms. The situation believed to be related is the determination of time delay from signals received by two physically-separated receivers. For example, one has exactly this situation when azimuth is determined by interference of the signals from two wingtip antennas. A favored modern way of making this determination is called "generalized correlation."

One short paper (Ref. 9) compares, on a normalized basis, the previously published results of several numerical simulations of generalized correlation. Despite some variations in the algorithms and assumed signals, the normalized results for the variance in time estimate tend to cluster in a systematic way, for SNR's varying from much less than to much more than 0 dB.

This two-signal case is likely to be indicative of the situation for one-signal processing of the sort that we are designing, according to the following argument that applies to a single brief event. Such a signal could be divided into two copies. (The signal capture will have been triggered by the direct-path signal because it arrives first.) One copy of the signal could have its earliest part strongly diminished (very easily in digital processing). Then this signal could be cross-correlated with a copy of the original signal (with or without a diminution in the later parts of this signal). Then the performance should correspond in some degree to the generalized correlation results.

The time-gating which has been mentioned is more of a reasoning tool than a needed suggestion and, in any

event, would not be appropriate for a storm producing signals that lasted for longer times than the path difference. Having more signal is not a problem, of course; it just means that the somewhat more limited noise theory developed for cepstrum calculations must be relied upon.

Further, these considerations suggest that the time window and perhaps other details of the processing preferably should be adaptive to some degree, according to the nature of the signals. The digital computer is suitable not only for making this adjustment but for reanalyzing the data with the modified time window.

When all is said and done, the design for an SNR of at least 10 dB and preferably 20 dB will be as close to being correct as any estimate that can be made of SNR. The time window should minimize the intake of noise when there is no signal but must not unfairly abbreviate the delayed signal relative to the direct signal.

Because lightning is a strong signal -- when it occurs -- the truncation error of the analog-to-digital converter (ADC) can be the dominant signal uncertainty or "noise." Thermal noise is not likely to be important and receiver noise can be made even smaller than thermal noise. The ADC "noise" is largely a question of the cost of the converter.

Analog-to-Digital Converter Specifications

The sampling rate required follows rather directly from the desire to measure time delays down to 0.5 microseconds. The corresponding fringes will have a spacing of 2 MHz in the spectrum and at least three complete fringes seems to be an ungenerous but tolerable minimum number of fringes upon which to base the determination. Thus, a signal bandwidth of 6 MHz is specified. The sampling theorem requires a minimum sampling rate of 12 megasamples per second, but all experience teaches that a liberal factor of safety is needed to obtain sound results in the presence of significant noise. Therefore, a sampling rate of 36 Ms/s is suggested.

This factor of safety in sampling rate mentioned in the previous paragraph is a primal requirement for having data worth processing. For a given sampling rate, the cost of the analog-to-digital converter (ADC) rises rapidly with the number of bits of accurate resolution that it must provide. An estimate of this resolution will be made.

If all direct signals had the same magnitude, the signal-to-noise power ratio for the echo would be approximately $(2^n)^2$, reduced further by the square of A_1 (the relative strength of the echo, if not substantially equal to unity), where n is the number of bits. Although a 20 dB signal-to-noise ratio should be sufficient when the signal has the optimum amplitude, it is probalably

necessary to allow another 30 dB for signal level variations even when a compressive circuit precedes the ADC. Another 10 dB is appropriate to allow for fairly strong waves (i.e., $A_1 = 0.32$; see Fig. 4). The total is 60 dB, so that the above quantity should be set equal to one million.

The solution for n is then 10 bits. Thus, a 10-bit ADC with a 36 MHz sampling rate is suggested. Single chips with this capability should soon be available at gradually decreasing prices, considering prototypes that have been reported (Ref. 10). Television applications will drive this development.

A memory-less logarithmic amplifier characteristic should be obtainable at these frequencies by placing Schottky-diode limiters between some of the final gain stages preceding the ADC. In a final design that might place less reliance on adapting television component, logarithmic amplifiers using available fast transistors could accomplish the compression with sufficiently-low distortion. The anticipated signals will vary enough in strength from variations in distance to make this compression of dynamic range appropriate. By reducing the dynamic range from 30dB to 10dB, one might hope to increase the signal-to-noise ratio sufficiently to permit much swifter short-cuts in place of cepstrum processing. In Ref. 11, an interesting fast technique for inferentially separating the direct and delayed signals is proposed; it is only suggestive for our purpose because it presumes knowledge of the time difference.

Experiments on Lightning

We are undertaking to infer path differences without having an undisturbed copy of the signal entering the multipath situation. Such an inference is possible as long as the features introduced by the multipath are sufficiently distinctive.

We have observed natural lightning with a ground-based antenna connected to a fast digital oscilloscope, the Analogic Data Precision Model 6000, on loan for a limited period of time. With a delay line coupled to the antenna lead-in cable, a path difference of 0.2 microseconds was introduced -- a path difference corresponding, for usual altitudes, to ranges somewhat beyond those expected for the first prototype.

For one set of experiments, a 274 MHz receiver was connected to the antenna and its output was connected to the digital oscilloscope. The oscilloscope was triggered well enough by the signal received in the 2 MHz bandwidth of the receiver, but this bandwidth was not enough to resolve the 0.2 microsecond delay. It would have been desirable to contrive longer delays. But it was the only storm we had and attention was turned to using directly the 6 MHz baseband of the 12-bit 36 Ms/s plugin of the digital oscilloscope.

The spectrum of the combined signal clearly reveals the presence of the multipath, as shown in Fig. 6. The spectrum has substantial power at frequencies irrelevant to the intentional multipath, but the spectrum analysis segregates the interfering signals (which dominate the raw waveform) from the desired signal that appears at the expected frequency of 5 MHz.

Theoretically, autocorrelation contains exactly the same information as the power spectrum. However, the autocorrelation calculation, as performed by the built-in routine of this instrument on the same stored waveform, lacks distinctive features that can be attributed to the multipath. The autocorrelation calculation produces a very sharply-defined result, so that the minor waves in the curve of Fig. 7 may in principle contain extractable information on both the echo and the interference. However, the spectrum seems to be a much more tractable starting point for designing algorithms to isolate the desired information on time delay and is the approach recommended for Phase II.

These results are encouraging and the use of a 6 MHz band at a frequency intermediate between baseband and 274 MHz is expected to lead to more resolution and fewer interfering artifacts.

The routine availability of instruments that have more than adequate resolution (12 bits) at the desired sampling rate is technologically very encouraging. It is expected that cost can be reduced on operational models when the versatility of a laboratory instrument is not required, especially if logarithmic preprocessing can keep the required number of bits down to 10 or less.

In view of the similar bandwidth requirements, some attention was paid to the appearance of lightning on a television receiver. It was noted that the effects could be identified only when a broadcast station was being received. Then the broadcast was replaced with the channel 3 signal from a home computer. The carrier frequency is necessary for the functioning of the video detector. The synchronization pulses also have the useful effect of disciplining the raster pattern.

Electronic Components

The electronics of the system will include receiver, signal processing and display. It is reasonable to assume that the receiver will be analog in its first stages and that the signal processing will at some point become digital.

It is not necessary to go to high VHF frequencies to avoid confusion from ionospheric reflections, as the calculations on path differences have shown, with realistic values for a spherical earth and curved paths within the atmosphere. Lower frequencies will be found where interference is tolerable -- particularly in view of the fact that the lightning signal is much stronger at

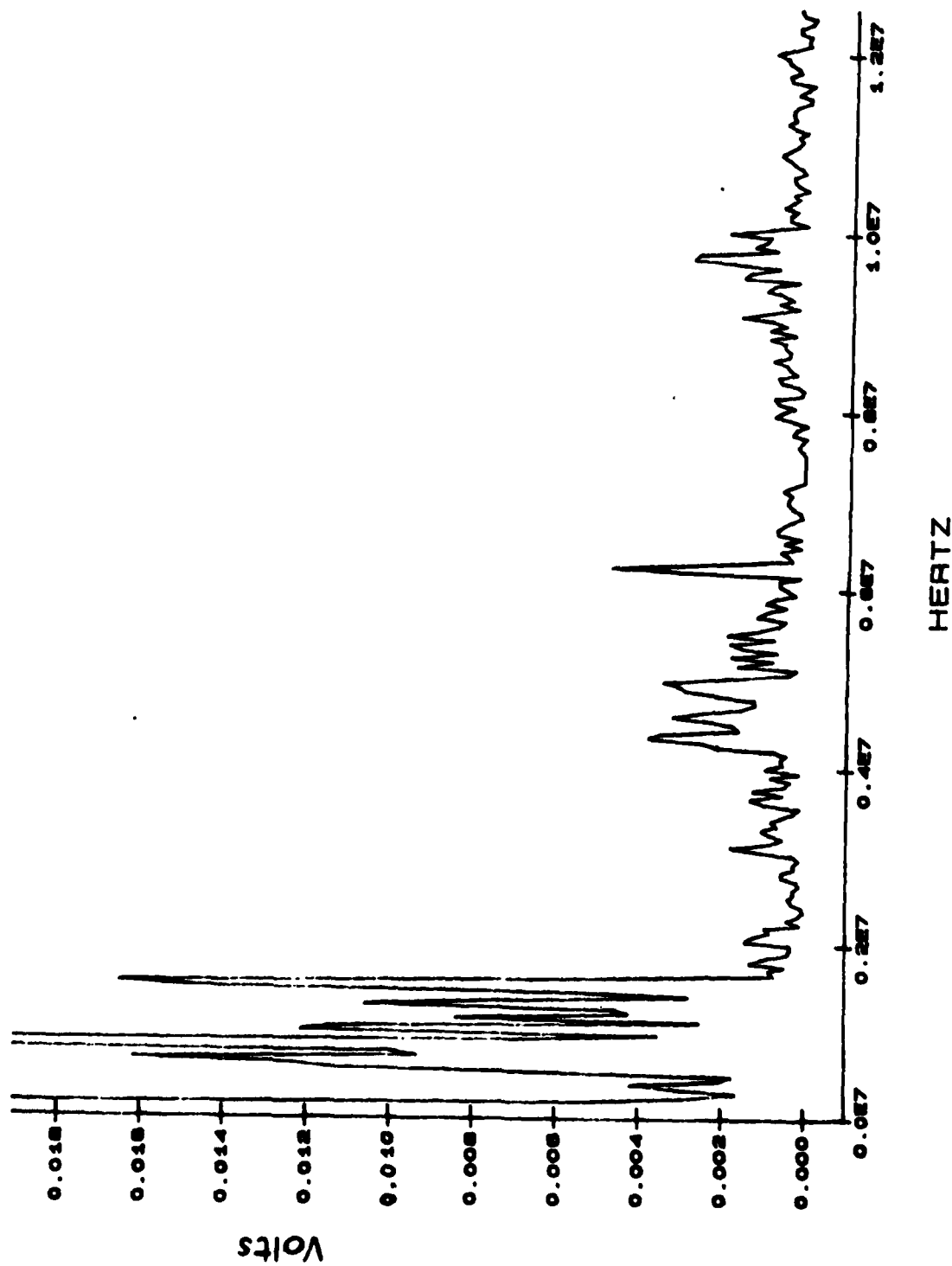


Fig. 6. Baseband spectrum of lightning with artificial 0.2 microsecond delay

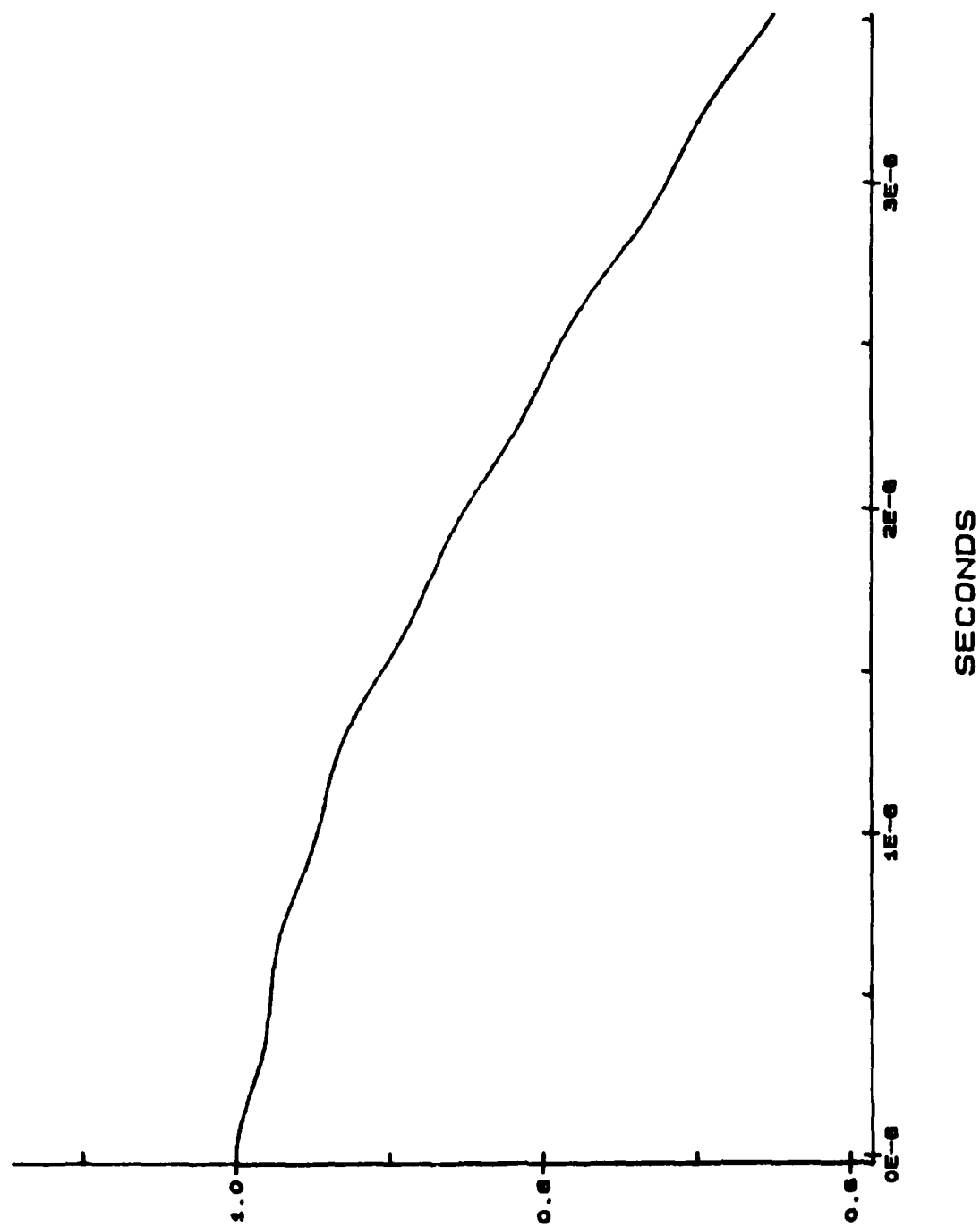


Fig. 7. Autocorrelation of lightning with artificial 0.2 microsecond delay

lower frequencies. At sea, the man-made interference should not be much of a problem. But even near shore (of the U.S.A. in peacetime, which might be thought to be a worst case), the FCC has taken pains to see that television channels 3 and 4 are not both in local use. Thus a 6 MHz clear channel should always be available in the 60 to 70 MHz region that seems suitable for our purpose.

A way to obtain an inexpensive receiver with about the right signal bandwidth and more than the required tunability is to use the receiver components mass-produced for television and video-tape recorders.

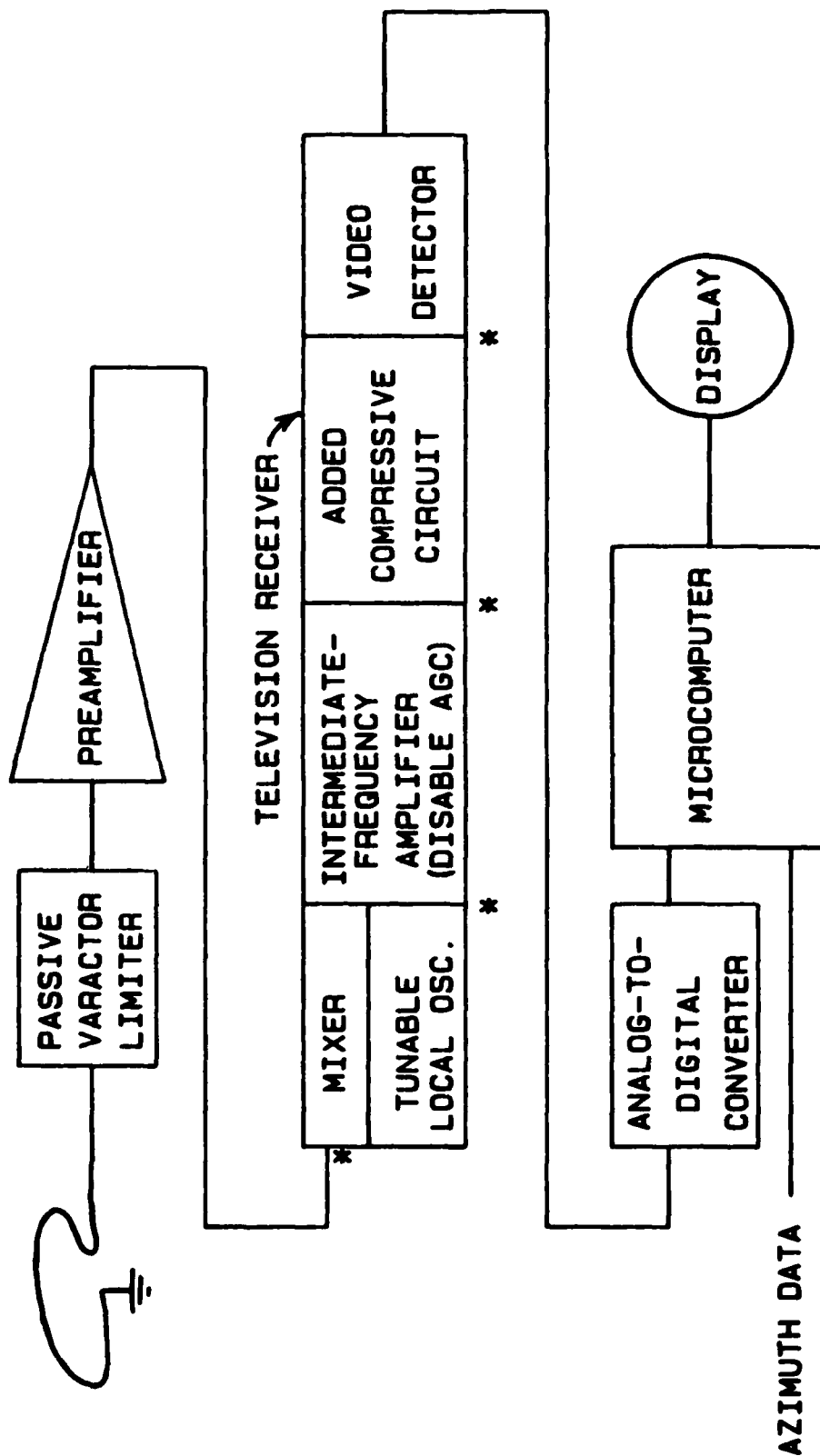
Television uses vestigial-sideband reduced-carrier modulation. The reduced carrier is, nevertheless, the most prominent characteristic of the received signal as viewed on a spectrum analyzer and is necessary for the operation of the detector that converts the intermediate-frequency signal to the baseband video signal. Lightning does not come with a carrier. This condition can be dealt with by adding a carrier, generated by a local oscillator, at almost any point up to the input to the detector. As noted in the section on experiments, the television interface of a personal computer provides enough carrier power to activate the detector. Alternatively, the detector could be replaced by a true mixer to shift the received signal to or near baseband. A second local oscillator would still be required. Either arrangement is capable of preserving the echo information.

Signal processing will operate on the baseband signal. (In theory, the bandlimited signal could be sampled directly, without conversion to baseband, but such an arrangement would place excessive demands on the perfection of the sampling characteristics of the ADC.) The digital oscilloscope that we have tested, with 36 MHz sampling rate, matches very well the 6 MHz baseband signal that is expected.

A diagram of the system that has been discussed is given in Fig. 8. The combined block of mixer, tunable local oscillator, intermediate-frequency amplifier, and detector is the front-end of a television receiver. One might even consider using the picture tube and deflection circuits of a small-screen television set as a display unit. In effect, the signal is detoured through a computer, the arrangement otherwise resembling a television set. It is unlikely that the limiter, the preamplifier, and the compressive circuit will be adapted from television accessories; suitable circuits can be constructed from inexpensive semiconductor devices.

The use of digital processing permits the characteristics of a simple diode compressing circuit to be stored and allowed for in the calculations. The microcomputer indicated in Fig. 8 would be a complete system for prototype testing. Production models would use microprocessor chips and would not need keyboards or

RANGING ANTENNA



* ALTERNATIVE LOCATIONS FOR CARRIER INJECTION

FIG. 8 INTERFEROMETRIC LIGHTNING RANGING SYSTEM

disc drives.

The digital oscilloscope shows that very satisfactory analog-to-digital conversion is technically possible in reasonably small packages. The only issue we have to face is how to obtain this performance at low cost. Generally, requirements for many bits of resolution greatly increase the cost of analog-to-digital converters. Analog compression before the ADC is expected to keep the bit requirement from expanding unduly as signals of widely varying strengths are encountered.

Analog-to-digital converters of nearly the required performance have been fabricated in monolithic chip form (Ref. 10) and chips with even better performance are now said to be available in prototype form. The initial price of samples was several thousand dollars and these chips probably go beyond the present need in accuracy. Presumably, single-chip devices will eventually be relatively inexpensive; we would naturally use less integrated circuitry if that did not prove to be true. Our application requires resolution, speed and reasonable monotonicity, but not absolute accuracy because consistent errors can be accounted for in the same way that allowance is made for the characteristics of the analog compressive circuits.

The required signal processing should be no problem for the fast microcomputer chips that are used in recently-introduced personal computers. A computer with more versatility than required for the final design would provide flexibility in testing signal processing for operation over land, where the echo will not be as strong and where the elevation of the terrain must be taken into account. It is now possible to choose such a computer based on a microprocessor available for incorporation in a final dedicated system, to minimize the need for translating algorithms that are developed.

Conclusions

The bandwidth required to derive lightning range by multipath interference is comparable to that used in television. The interference effect that is exploited in this determination will be very pronounced over water. When the water is the sea, the altitude of the reflecting surface will be known exceedingly well and the altitude of the aircraft should be known with good accuracy.

The approximate formula for range has been shown to hold well enough over most of the ranges of interest to be used for error estimation. It indicates that the relative error in range will be essentially the same as the relative error in estimation of the height of the cloud discharge.

The height of the lightning source can be estimated from climatological data and it is expected that this estimate can be further refined from the prevailing

meteorological data available from on-board instruments. As will be explained in greater detail in the Phase II proposal, research now in progress is establishing relationships between space charge in thunderclouds and their temperature structure.

The interference effect will not be as strong over land and the altitude of the reflecting land surface will be needed to compute the range. This information will be available to the pilot and can be entered into the instrument.

Flyable prototype systems can be quickly assembled out of analog components that are relatively inexpensive, together with general-purpose digital instrumentation that would be replaced by much less expensive dedicated microprocessors after the best signal-processing algorithms are selected from tests.

References

1. H. R. Reed and C. M. Russell, "Ultra High Frequency Propagation," 2nd ed., Boston Technical Publishers (Lexington, MA, 1964)
2. R. J. Papa, K. V. N. Rao, J. F. Lennon, and J. W. Coffey, "A Survey of Terrain Scattering Theory and Measurements for Air Force Systems," RADC-TR-84-78 (April, 1984) Export control through RADC(EECT), Hanscom AFB, MA 01731
3. W. I. Lam and A. R. Webster, "Microwave Propagation on Two Line-of-Sight Overseas Paths," IEEE Transactions on Antennas and Propagation, vol. AP-33, pp 510-516 (May, 1985)
4. P. Beckmann and A. Spizzichino, "The Scattering of Electromagnetic Waves from Rough Surfaces," Macmillan, NY (1963)
5. J. C. Hassab and R. Boucher, "Analysis of Signal Extraction, Echo Detection and Removal by Complex Cepstrum in Presence of Distortion and Noise," Journal of Sound and Vibration, pp 321-335 (1975)
6. *ibid.*, "Improved Cepstrum Performance through Windowing of Log Spectrum," pp 597-598 (1978)
7. *ibid.*, "A Probabilistic Analysis of Time Delay Extraction by the Cepstrum in Stationary Gaussian Noise," IEEE Transactions on Information Theory, vol. IT-22, pp444-454 (July, 1976)
8. *ibid.*, "Further Comments on Windowing in the Power Cepstrum," Proceedings of the IEEE, vol. 66, pp1290-1291 (October, 1978)
9. R. L. Kirlin and Jonathan N. Bradley, "Delay Estimation Simulations and a Normalized Comparison of Published Results," IEEE Transactions on Acoustics, Speech, and Signal Processing, vol. ASSP-30, pp508-511 (June, 1982)
10. M. Inoue, T. Takemoto, H. Sadamatsu, K. Aono, K. Tsuji, "A 10 Bit All-Parallel A/D Converter," Paper A-4-2, 14th Conf. (1982 International) on Solid State Devices, Tokyo
11. D. A. Ksienski, "A Method of Resolving Data into Two Maximally Smooth Components," Proceedings of the IEEE, vol. 73, pp166-168 (January 1985)

Appendix A: Program for Propagation Calculations

The variables used to represent quantities in the program are defined in the program. They are single characters followed (at most) by a single number. This restriction makes them acceptable to any BASIC interpreter. However, it also makes them harder to identify, so a table of symbols is given below in addition to the identification in program remarks.

The program is written in BASIC which differs from ANSI standard minimal BASIC in having more than one statement on some of the lines, with a colon as a separator. It will run as written on most personal computers, including all Commodore models before the Amiga. Some Hewlett-Packard BASICs require a "@" in place of the colon and VAX/VMS BASIC calls for a back-slash instead of a colon.

Enough unused line numbers are present so that the program can be written with one statement per line, as required for some versions of BASIC.

Statements can be added in the usual way to cause the calculation to loop on successive values of grazing angle and other variables. Also, additional statements are usually needed to direct the output to a printer. The print statements can be rewritten to produce tables in any desired form.

The calculations are sufficiently rapid that there is little advantage in bypassing the calculation of results that are not wanted in a table, especially in view of the fact that some of the calculated quantities are used in subsequent calculations.

"Scratch variables" are intermediates in calculations and are the only ones that may be reused; all of the others retain their assigned values. Range is converted to nautical miles in the PRINT statement.

Symbol Table

A radians on $4/3$ earth from source to reflection point
A1 magnitude of reflection, horizontal polarization, smooth sea.
A2 ibid., rough sea
A3 ibid., vertical polarization, smooth sea
A4 ibid., rough sea (nominal, not plotted)
B radians on $4/3$ earth from reflection point to receiver
C cosine of the grazing angle
D range at sea level, feet
D1 divergence power reduction factor
E1 relative dielectric constant of sea water (real part)
F frequency in megahertz
G grazing angle in radians

G1 grazing angle in degrees
 H average height of source and receiver, feet
 H1 height of source, feet
 H2 height of receiver, feet
 I0 ionospheric reflection path difference, feet
 I9 ionospheric height, feet
 L direct path from source to receiver over $4/3$ earth, feet
 N half-angle of range on true earth, radians
 O scratch variable
 O2 roughness factor, power ratio
 P scratch variable
 P0 path difference, feet
 P9 approximate path difference, feet
 Q scratch variable
 R $4/3$ earth radius, feet
 R0 true earth radius, feet
 R1 path length from source to reflection point, feet
 R2 path length from reflection point to receiver, feet
 S sine of the grazing angle
 S1 conductivity of the sea, mhos/meter
 U,V scratch variables
 W1 peak-to trough wave height, feet
 W root-mean-square wave height, meters
 X,Y scratch variables

```

10 REM PATH DIFFERENCES AND PROPAGATION CALCULATIONS
110 P5=1.57079633:REM PI/2
120 R=5280^2:R0=.75*R:REM 4/3 & 1.0 EARTH RADII, FT
130 E1=80:REM DIELECTRIC CONSTANT
140 S1=4: REM CONDUCTIVITY, MHOS/M
160 F=60:REM FREQUENCY, MHZ
170 W1=20:REM PEAK-TO-TROUGH WAVE HEIGHT, FT
180 I9=2E5: REM IONOSPHERE HEIGHT, FT
190 :
200 G1= 6:REM GRAZING ANGLE, DEGREES
210 G=P5*G1/90:C=COS(G):S=SIN(G)
220 REM ROUGHNESS FACTOR, POWER RATIO
230 W=.0644*W1:O=8*P5*S*W*F/300:O2=EXP(-O^2)
240 :
250 REM REFLECTIVITY, POWER RATIO
260 X=18000*S1/F:Y=E1-C*C
270 P=SQR(Y*Y+X*X):Q=S*SQR(2*(Y+P))
280 P=P+S*S:G2=(P-Q)/(P+Q): REM HORIZ. POL.
285 U=(E1*E1+X*X)*S+P/S
290 V=E1*SQR(2*(P+Y))+X*SQR(2*(P-Y))
295 G3=SQR((U-V)/(U+V)):REM VERT. POL.
300 :
310 H1=20000:H2=20000:REM SOURCE AND RECEIVER HEIGHTS, FT
315 :
320 REM RANGE D AND PATH DIFFERENCE P0, FT
330 Y=C/(1+H1/R):X=SQR(1-Y^2):A=P5-G-ATN(Y/X)
350 R1=SIN(A)*(R+H1)/C
360 Y=C/(1+H2/R):X=SQR(1-Y^2):B=P5-G-ATN(Y/X)
380 R2=SIN(B)*(R+H2)/C
390 L=((R+H1)*COS(A)-(R+H2)*COS(B))^2
400 L=SQR(L+((R+H1)*SIN(A)+(R+H2)*SIN(B))^2)
410 P0=R1+R2-L:D=(A+B)*R
450 :
460 P9=2*H1*H2/D:REM APPROX. PATH DIFF., FT.
500 :
510 D1=1/SQR(1+2*R1*R2*C/D/R/S):REM DIVERGENCE FACTOR
515 :
520 REM VOLTAGE REFLECTION FACTOR
530 A1=SQR(D1*G2)/(1+P0/L):A2=A1*SQR(O2):REM HORIZ. POL.
532 A3=SQR(D1*G3)/(1+P0/L):A4=A3*SQR(O2):REM VERT. POL.
540 :
550 H=(H1+H2)/2:N=D/R0/2
560 U=(R0+H)*SIN(N):V=I9+R0*(1-COS(N))
570 I0=2*(SQR(V*V+U*U)-U):REM IONOSPHERIC PATH DIFF., FT.
600 PRINT "GRAZING ANGLE,H1,H2 = ";G1;H1,H2
700 PRINT "PATH DIFF, FT = ";INT(P0+.5)
710 PRINT "RANGE,NM = ";.1*INT(D/607.6)
720 PRINT "DIVERGENCE FACTOR = ";.0001*INT(10000*D1)
730 PRINT "REFLEC. PWR. COEF (H) = ";.0001*INT(10000*G2)
735 PRINT "REFLEC. PWR. COEF (V) = ";.0001*INT(10000*G3)
740 PRINT "SMOOTH ECHO VOLTAGE RATIO (H) = ";.0001*INT(10000*A1)
745 PRINT "SMOOTH ECHO VOLTAGE RATIO (V) = ";.0001*INT(10000*A3)
750 PRINT"ROUGHNESS FACTOR FOR";W1;"FT WAVES = ";.0001*INT(10000*O2)
760 PRINT "ROUGH ECHO VOLTAGE RATIO (H) = ";.0001*INT(10000*A2)
765 PRINT "ROUGH ECHO VOLTAGE RATIO (V) = ";.0001*INT(10000*A4)
770 PRINT "APPROX. PATH DIFF., FT = ";INT(P9+.5)
780 PRINT "IONOSPHERIC DELAY, FT = "; INT(I0)
800 PRINT:END

```

READY.

D. RECOMMENDATIONS FOR PHASE II

-- Radioactive Probe D.C. Electric Field Sensing System

For reasons discussed above it is recommended that instrumentation capable of measuring d.c. electric fields be developed during Phase II using radioactive probes with impact shields. This instrumentation would allow detection of dangerously charged clouds which are not producing lightning. It would indicate proximity to clouds that may be developing high electric fields and provide warning before the lightning stage is reached or before the aircraft might trigger lightning. It would also show that the aircraft was approaching hazardous regions near clouds with lightning as illustrated by Fig. 6. Most intercloud lightning is not visible in daylight.

Because we have experience developing and operating aircraft radioactive probe systems over the last 15 years and have already developed servoed high voltage electrometers which proved to be trouble free during the Phase I testing, only modest effort would be required to test the improved instrumentation with impact shields during Phase II interferometer test flights. By measuring the potential between a probe at each wingtip, the sensitivity can be increased by a factor of about 30 due to the concentration of electric field lines at the wingtips. This will provide the lateral electric field component to complement the vertical component measured with the vertical probe array. It is likely that the d.c. electric field instrumentation would function in cloudy air, but the extent to which hydrometeor impact might affect the measurements is still to be determined. Even if the electric field measurements are adversely affected by hydrometeor impaction, most IFR flying is not conducted in precipitation. Thus, the ability to sense the direction and build up of electric fields and lightning in the vicinity of the aircraft would provide useful information to pilots for avoidance of dangerous regions. Additional details regarding the planned testing and evaluation of electric field instruments by pilots of different aircraft will be given in the Phase II proposal.

-- Lightning Interferometer

The use of lightning produced RF signals for thunderstorm avoidance is by now well proven and accepted; over 10,000 Stormscope systems have been sold during the last 10 years. Recently the original company has been acquired by a large corporation to expand sales. Purchasers of some new single engine aircraft (e.g., Mooney) are picking the Stormscope as an original equipment option in preference to radar for storm avoidance by a factor of 2:1 (Business and Commercial Aviation, March 1986, p. 72). This is because radar antennas of sufficient vertical dimension will not fit into the wing leading edge, the nose is unavailable for a radar dish, and drag producing external pods to house sufficiently large radar antennas are undesirable. In addition, as discussed in the original proposal, many believe that lightning mapping is better than radar for thunderstorm avoidance. Some of the same considerations apply to modern military aircraft that generally have thin wings and use their nose compartments to carry armaments or electronic countermeasure antennas rather than weather radar. As previously suggested, the best possible

arrangement would be for aircraft to have both radar and lightning mapping/electric field equipment since each has particular advantages over the other depending on atmospheric conditions.

At present the only product available utilizing lightning produced signals for aircraft thunderstorm avoidance is the Stormscope. The major problem with this system is that it estimates the range of the lightning from signal intensity, i.e., the assumption is made that distance is essentially inversely proportional to signal strength. Thus strong emitters appear farther away and weak ones nearer than they really are. The survey of aircraft lightning detection technology by Parker and Kasemir (cited earlier) discussed this ranging limitation plus azimuth error due to the assumption that the lightning flash is vertical (which generally is not the case) and azimuth error from the location of the antenna on the airframe. An evaluation of the Stormscope by Fisher and Crabill (cited earlier) reports significant inaccuracies in lightning range. A recent discussion with B. Fischer (Flight Applications Branch, NASA/Langley Research Center, Hampton, VA) who has been comparing a ground based Stormscope with satellite cloud images, indicates that the Stormscope frequently shows lightning far from any cloudy regions. The proposed lightning interferometer will acquire range by geometry, is insensitive to lightning orientation or aircraft antenna location, has better signal-to-noise ratio and offers additional advantages as a new technique for accurate lightning mapping. Details will be given in the Phase II proposal.

END

FILMED

6-86

DTIC